Final Report

FORCE/TACTILE FEEDBACK SYSTEM FOR VIRTUAL REALITY ENVIRONMENTS

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13. ABSTRACT (Maximum 200 words)
TOPIT™ - Touch Objects Positioned In Time, is a vitural reality system that allows a user, wearing a head mounted display (HMD) to actuate control knobs or dials on a cockpit instrument panel appearing in user's HMD. The actual control knobs/dials are delivered to the user by an x-y-z robot. The instrument panel can be reconfigured entirely in software. A tracker and data glove continually provide the position of user's hand and finger to a computer, and the computer commands the servomechanism system to place the correct type of control in the correct position to be actuated. The servo system has a "touch panel" that contains examples of a dozen or so different types of controls, such as toggle switches, knobs, and push buttons, that are used repeatedly to represent any number of instrument panel controls. One key aspect of the system is building a servo system that moves fast enough to put the knobs/dials in place at the time when the user reaches for it. Another key aspect is achieving precise low-latency tracking of both user's head and user's hand.

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1. Introduction

The top-level objective of this SBIR Phase II project was to build a prototype virtual cockpit that included force and tactile feedback. We achieved this top-level objective and all key technical objectives discussed in section 2 as well. We discuss more of each of the technical objectives and our approach in detail later in the report when we present our system concept in Section 3, and Phase II results in Section 4.

System overview and project accomplishment

The user wears a head mounted display that presents stereo imagery of a cockpit interior, including the instrument panel, as well as the out-the-window scenery. A representation of the user's hand is also rendered in the scene. The user may actuate a variety of controls on the instrument panel, and can accurately feel the forces and surface textures of the controls. The simulator can be reconfigured entirely in software to represent different cockpits. The feel of the instrument panel controls is provided by a servomechanism device that places actual physical controls in their correct positions, orientations, and configurations. A tracker and data glove continually provide the position of the user's hand and fingers to a computer. The computer senses the position as the person reaches for a control. Using the extrapolated data, the computer commands the servomechanism system to place the correct type of control in the correct position to be actuated. The servo system has a "touch panel" that contains examples of a dozen or so different types of controls, such as toggle switches, knobs, and push buttons, that are used repeatedly to represent any number of instrument panel controls.

The system is called a TOPIT™ - Touched Objects Positioned In Time. One key aspect of the system is building a servo system that moves fast enough to always have the control in place before the user's hand reaches it. Another key aspect is achieving precise low-latency tracking of both the user's head and the user's hand. The tracking must be accomplished in the presence of the moving metal elements and the electric motors of the servo system; a hybrid magnetic/inertial tracker was developed to meet these requirements. The system has three computers: an SGI Onyx/RealityEngine2 that does the imagery, a Pentium-based PC that does the tracking, and a VME-based servo control system.

The TOPIT Force/Tactile Feedback System concept drawing [Figure 1-1] shows the proof-of-concept demonstrator being used to simulate an aircraft cockpit. The central issue of the feasibility of the scheme is establishing and meeting the timing requirements for determining the touched-object and moving it into place in time.

However, while basic feasibility was established in Phase I, construction of a demonstrator during the Phase II effort required the careful design and integration of mechanical, electro-mechanical, and computer controlled devices to meet project objectives.

Overall, the major technical challenges were met. In particular, robotic hardware was built to position the controls with the speed and accuracy required, and a sophisticated tracker and an alternative tracker were built to provide the accuracies required for position and extrapolation. The most difficult aspect of the program turned out to be getting all of the bugs out of the complex system under severe budget constraints. In this last respect we were largely successful, but not entirely. The main limitations of the final prototype lie in the fine points of getting the software to run completely smoothly and reliability. We view none of the present limitation as being fundamental.

Report organization

Section 1 presents an overview of the project and snapshots of subsystems and components the prototype developed. Section 2 discusses the technical objectives of the project. Section 3 discusses the system concept and implementation, and section 4 compares the results of the phase II effort to the objectives and the original designs for the project. Section 5 presents the conclusions.

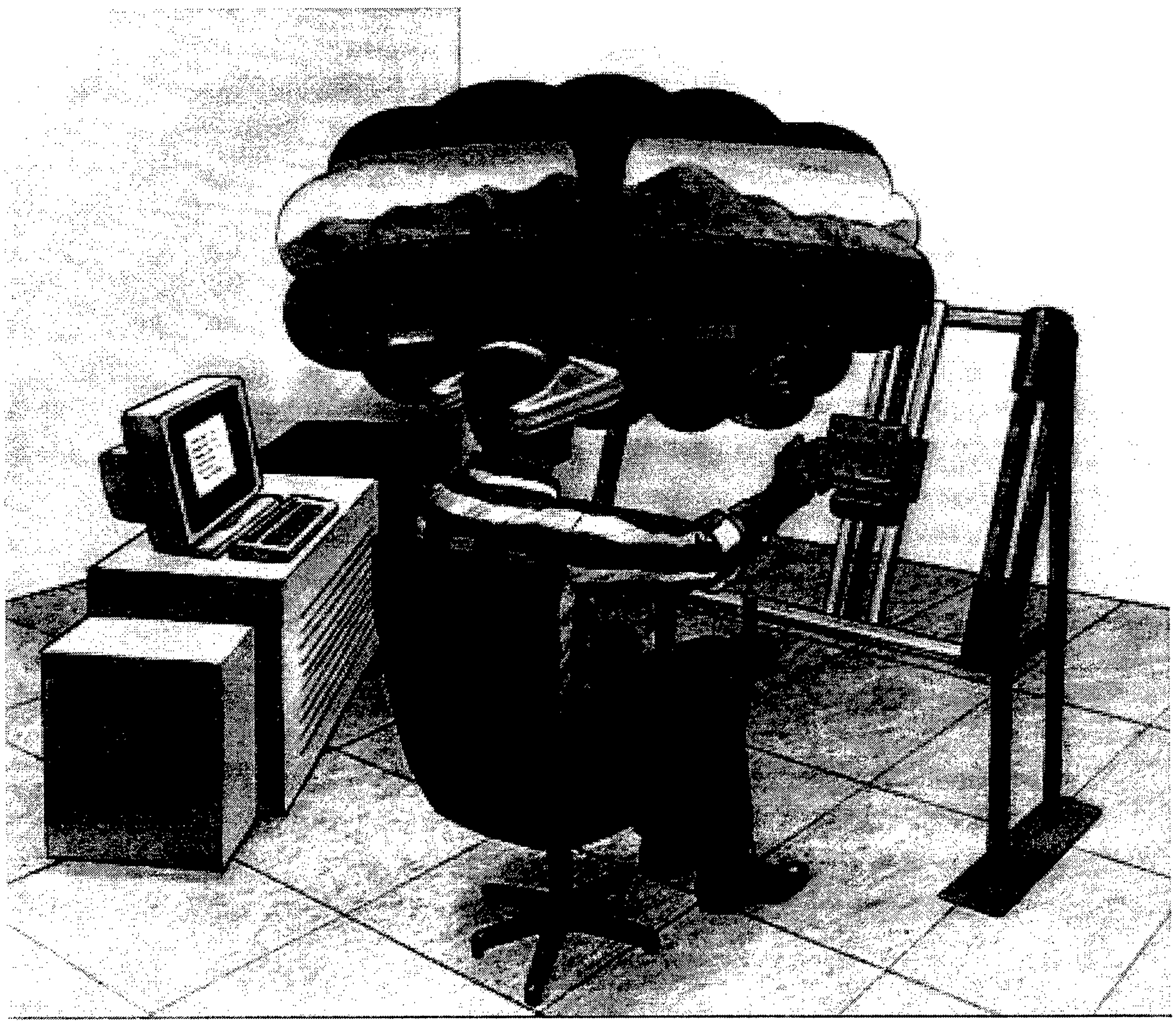

Figure 1-1 TOPIT concept. Physical switches and knobs are positioned in a virtual environment under software control to provide flexible force and tactile feedback.

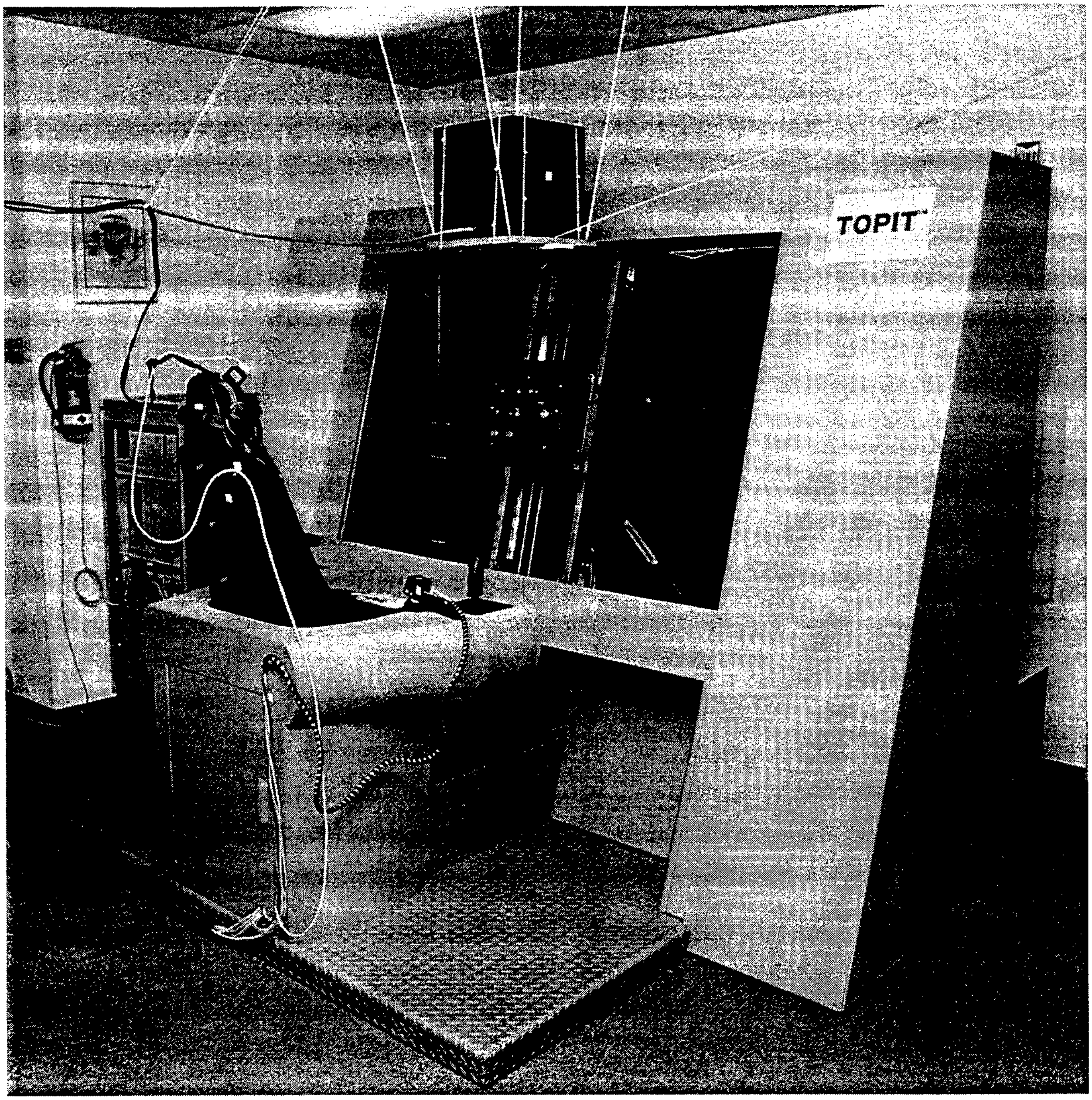

Figure 1-2 TOPIT Prototype.

Figure 1-3.1 User station showing joystick, throttle, instrumented glove, and helmet-mounted display.

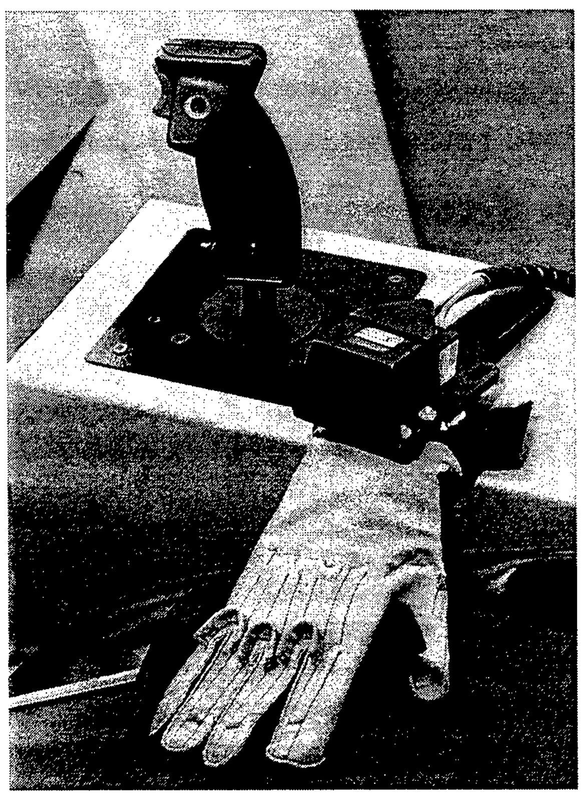

Figure 1-3.2 Joystick and instrumented glove.

Figure 1-3.3 Multisensor.

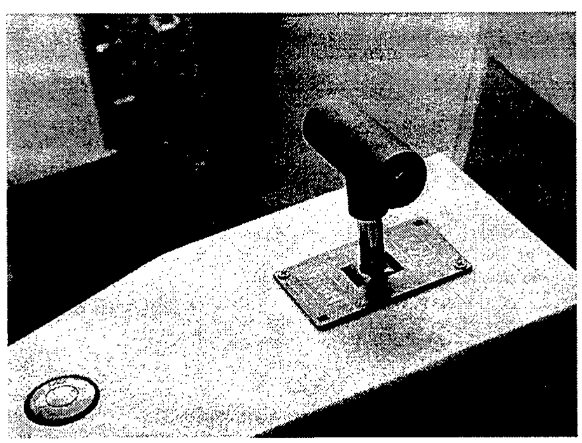

Figure 1-3.4 Throttle and emergency stop button.

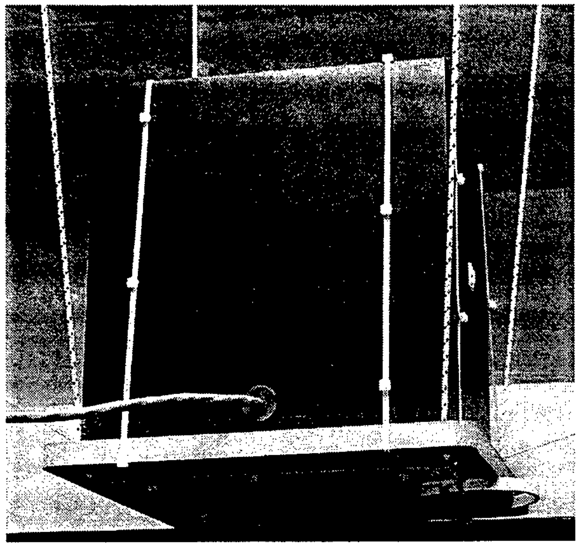

Figure 1-3.5 Magnetic tracker transmitter.

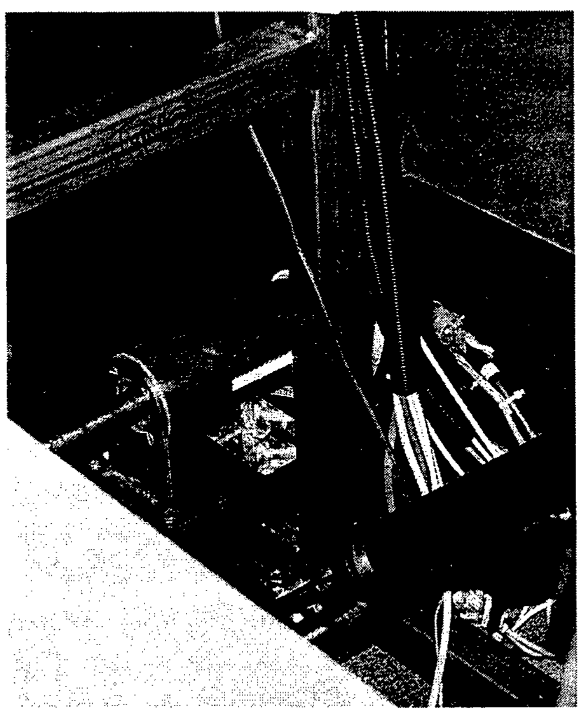

Figure 1-3.6 Y-axis servo motor.

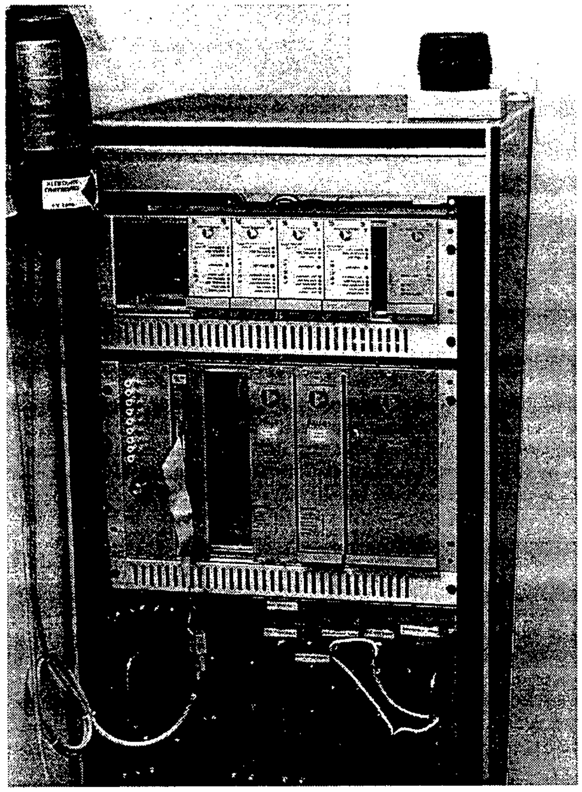

Figure 1-3.7 Servo electronics cabinet.

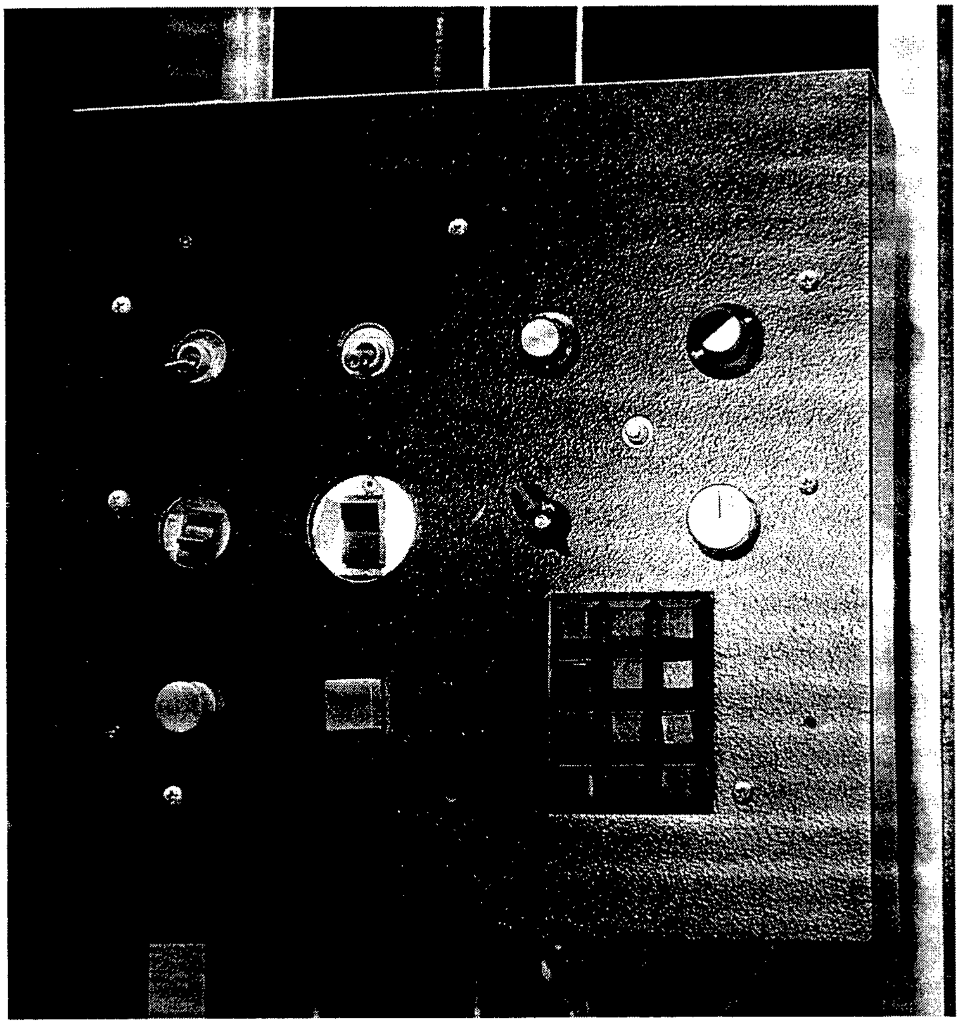

Figure 1-3.8 Touchpanel.

2. Summary of Technical Objectives and Approach

The primary objective of the Phase II effort was to design, construct, and evaluate the TOPIT force and tactile feedback system through a complete implementation of a virtual cockpit. We considered developing a partial implementation, without the visual simulation of the virtual environment. The visual environment, however, was necessary to guide the user to each specific point in virtual space where a virtual control was located. Without the visual simulation, the touchboard could only be guided to mirror hand and finger position, and the demonstration would miss the whole aspect of predicting hand trajectory, selecting the correct control, and fixing the control position in time to be touched. Also missing would have been the aspect of treating head tracker and image generator delays. With so much missing, we concluded that a partial implementation would be unconvincing in proving the TOPIT concept. The approach we adopted paid special attention to the risk areas identified in the Phase I study. The risk areas, identified in the Phase II proposal, and our approach to each key risk area were as follows:

(1) We wanted to build a positioning system that **moved fast enough**, but without excessive size, power, or cost was to be approached through a combination of rapid prototyping, in which the linear transport mechanism for the x-axis positioning was built experimentally using stepper motor and servomechanism implementations, and payload weight was minimized through careful design that encompassed the use of lightweight materials.

(2) We needed to ensure the tracking system provided **sufficient accuracy** in the presence of the electromagnetic noise and moving metal objects of the positioning system was approached by use of a pulsed rather than continuous wave tracker, synchronization of tracker pulses between motor steps, noise minimization by shielding, and by careful tracker transmitter placement. If problems persisted, a noise immune, but somewhat encumbering, mechanical tracker was to be used to support development.

(3) We needed to design hand motion prediction algorithms that predicted which control would be touched while sufficient time remained to put it in place was first approached at the system level using the basic hand motion data obtained in Phase I. These data bound the performance of the algorithm. However, considerable experimentation were made to fine tune the algorithms. Also, an alternative tracking system was developed that minimizes the need for such prediction algorithms.

(4) Keeping computation and control **lags small enough** so that the positioning system had sufficient time to position the touchboard was a fundamental systems engineering task required careful accounting of each time lag in the system. Continual refinement of the timing budget allowed early identification of problems. Computational problems could be treated by using dedicated board level processors for the control algorithms, by microcoding key computations, and by using interrupt-driven synchronized event processing.

(5) Providing redundant **safety** systems to protect the operator during development and use was considered to employ software to ensure the positioning system is commanded to stop before the tracked hand moves into the motion space, an independent light curtain electronic system that directly shuts down the system upon any intrusion into the motion

space, and mechanical guards around the working mechanisms to ensure than intruding elements were deflected rather than caught or pinched.

The identified technical risks made the Phase II implementation a major systems engineering challenge. Along with the direct risk of meeting the technical objectives was the associated risk of keeping the project on schedule and within budget as the various challenges were faced. The results are presented in the following two chapters.

3. System Concept

A traditional flight simulator is built using a replica of the cockpit of the aircraft being simulated. Building a replica cockpit is expensive, as a different replica cockpit is needed for every type of aircraft to be simulated, and it is difficult to keep up with changes made to the real aircraft. Conceptually, it would be better to have a virtual cockpit in which the elements of the cockpit are determined entirely by software. Then the expense of constructing physical replicas could be saved, one simulator could be used for many different types of aircraft, and after the simulators are in service the simulators could be quickly updated to reflect modifications in the real aircraft.

For a virtual cockpit, the appearance of a cockpit can be represented by computer generated imagery on a head-mounted display (HMD) worn by the user. The fidelity of this approach is limited by the resolution of the HMD and by the realism of the computer generated imagery for the display. HMD technology and image generator technology are such that the best currently available technology is probably barely acceptable for the application, and even then at relatively high cost. However, current trends toward lower cost and improved performance should close the performance gap considerably within a few years' time.

In addition to a visual simulation, a virtual cockpit also needs a simulation of the force and tactile sensations of touching the controls. The controls include the primary controls and the instrument panel controls. The primary controls are the joystick and rudder pedals or their equivalents for steering the aircraft. The instrument panel controls include switches, knobs, push buttons, and keypads. Replica controls could be provided to be used with the simulated imagery, but doing so would not meet the objective of having a simulator that is reconfigurable in software.

For the prototype virtual cockpit discussed here, replicas were used for the primary controls, but a software reconfigurable approach was adopted for the instrument panel controls. Because the simulator user is wearing a head-mounted display, and because the user touches only one instrument control at a time, it suffices to present to the user only the single control being touched. This is accomplished by using a collection of about a dozen different types of physical replicas of controls, and putting the correct type into the correct place to be touched whenever the user actuates a control.

To select the correct type of control and put it into place, the user's hand and fingers must be tracked and the positions extrapolated forward to determine which control will be grasped. A robotic mechanism then quickly puts the correct type of control into place in time to be actuated. A user may believe that different toggle switches are being flipped at different places on the instrument panel, but in fact the same toggle switch is being touched in all the different positions. A mechanism must be provided to put the switch in the correct "up" or "down" position while the switch is being moved to a new position. Similarly, rotary controls must be brought into correspondence with the way each control appears in the user's HMD imagery.

For the concept to be practical, the few replica controls must be moved rapidly to stay ahead of the user's hand motions. The requirements were quantified by analyzing cockpit videotapes taken in flight and also videotapes taken in a lab setup. In the lab, a number of non-pilot subjects were videotaped as they actuated switches and knobs in a prescribed sequence. Timing requirements were determined by stepping through the videotapes frame-by-frame and recording the times required to reach the controls. The derived requirements were that the controls must be repositioned with an acceleration of up to four g's and a speed of about three meters per second. Maximum acceleration and deceleration are required when closely-spaced controls are actuated in sequence.

3.1 System Configuration

The system is designed with three major subsystems, one each for robotics, tracking, and visual simulation [Fig. 3.1-1]. Each subsystem is controlled by its own computer, with communications links transferring data among the three control computers.

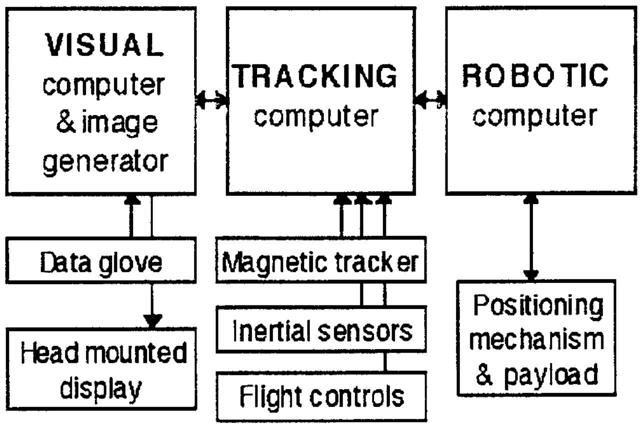

Figure 3.1-1 Three major subsystems.

The tracking subsystem is built around a personal computer running the QNX real time operating system [Figure 3.1-2]. The tracking computer interfaces with the hardware that measures the position and orientation of the user's head and right hand and runs software that filters and extrapolates the tracking data. It determines which switch the user is about to actuate and sends commands to the robotics subsystem to move the selected switch into place. It keeps track of the orientations to which the knobs and toggle switches are moved. It also interfaces to the user's flight control joystick and throttle and computes the position of the simulated aircraft. The tracking computer sends the positions and orientations of the head, hand, and switches to the visual simulation subsystem, which in turn generates imagery for viewing in the user's HMD.

The robotics subsystem includes a VME-rack with a control processor and interfaces, servo power supplies and amplifiers, and power distribution circuitry. The VME-based control processor receives high level commands from the tracking computer over a 38.4 Kb serial interface. The commands from the tracking computer instruct the robotics subsystem to move each of the servo-driven positioning mechanisms to prescribed locations or orientations. The robotics control processor carries out the commands by generating control voltages for each of the servo-motor amplifiers. The motors are equipped with digital shaft encoders and each motor channel is run closed-loop with an update rate of approximately 100 Hz. Each channel is tuned for the inertia and spring constants associated with the channels' hardware.

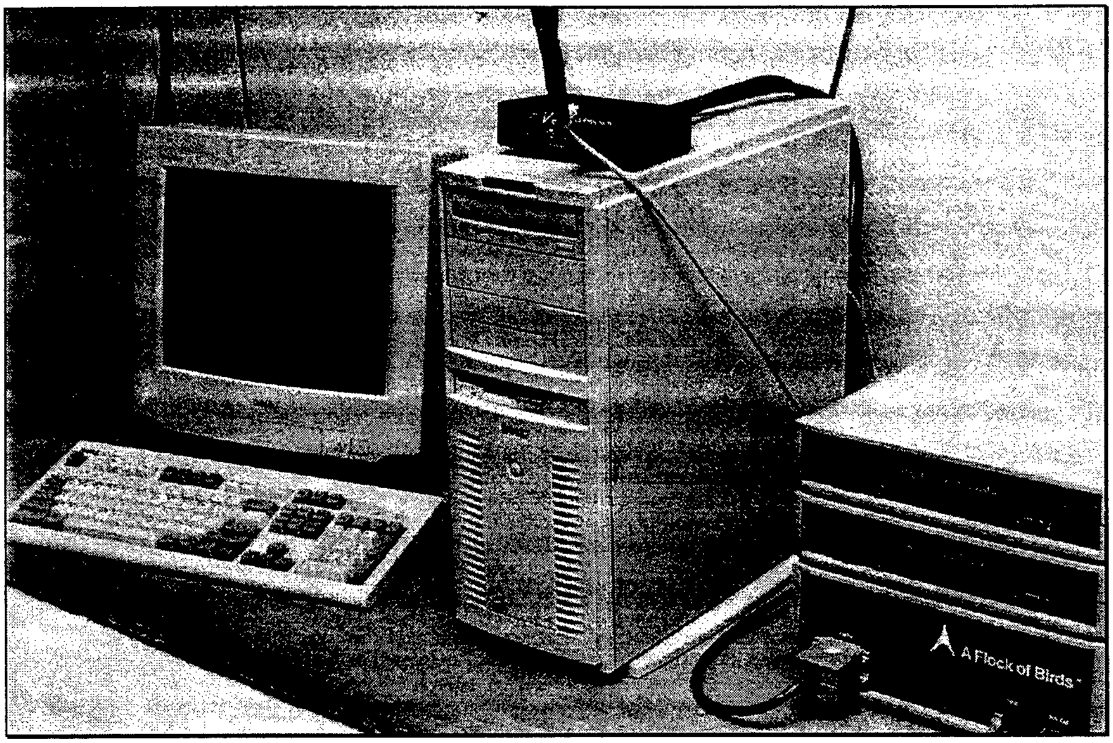

Figure 3.1-2 TOPIT tracking computer, magnetic tracker electronics (right) and HMD electronics (on top of computer).

The visual subsystem is built around a Silicon Graphics Onyx computer having a RealityEngine2 image generator. The visual computer receives data from the tracking subsystem over a dedicated Ethernet link having less than one millisecond latency. The visual computer has a database of polygons modeling the cockpit interior, the user's hand, and terrain outside the simulated aircraft. It assembles the scene from the polygon models, putting each model in its correct relative position. A dataglove worn by the user provides the positions of the fingers directly to the visual computer.

3.2 Tracker

Magnetic trackers are commonly used in virtual reality systems. They use compact, lightweight sensors, are unencumbering, measure all three position coordinates and all three orientation angles, and are economical. The limitations of magnetic sensors are that metallic objects distort the tracker fields thereby producing static errors, they are susceptible to interference from electrical noise sources, and there tends to be lags in the measurements. The lags come from filtering the noise inherent in the measurements. In many applications, none of the limitations prove severe. For the virtual cockpit, however, the tracking could not lag significantly and must work in the presence of the metal and motors of the robotic positioning device.

One alternative to magnetic tracking was mechanical tracking. A mechanical tracker uses stiff rods connected by joints having encoders. Mechanical trackers are low cost, extremely accurate, immune to noise, and have no appreciable lag. Unfortunately, mechanical trackers are encumbering since they require a mechanical linkage to the users head or hand. They are best used when the space of possible motion is small, and might be acceptable for head tracking a seated user. For hand tracking in a virtual cockpit, the encumbrance would not be acceptable in the long run. Nonetheless, mechanical tracking could be a backup method, at least for lab evaluation of the virtual cockpit.

There were a number of optical tracking systems available. These systems use a variety of principles for tracking. Some use high resolution cameras tracking reflective markers. Others use sensors that detect a scanning infrared laser. Optical tracking systems are typically so accurate that the orientation of a surface can be computed by tracking three points on the surface. Optical tracking would be a good choice for a virtual cockpit, but the cost of commercially available systems ruled it out for the prototype.

The alternatives were to work with the limitations of magnetic trackers or to attempt development of a low-cost optically-based tracking system. We opted to work with the magnetic tracker. To minimize magnetic field distortions, the robotic mechanism would have to be made from non-magnetic material. Aluminum was tested and found to be nearly as bad as carbon steel in inducing tracker distortions; it apparently induced distortions in the electric field component of the tracker transmission. The best metal was non-magnetic stainless steel (series 300), so that was preferred for construction. Wood or plastic might have been used, but the structure could not be made acceptably stiff.

As it turned out, the distortions due to the metal structure were up to about 4 cm of error, which could be reduced substantially by calibration and look-up tables. The goal was to provide overall tracking accuracy of about 5 mm, which seems achievable.

To treat the problem of tracker lag, an inertial sensor package was added to the magnetic hand tracker. The package initially consisted of three miniature accelerometers and three angular rate sensors. This inertial package was larger than desired, about three inches square and an inch think; however, it could be mounted on the forearm rather than on the hand itself.

The alignment of the axis of each sensor was required to be orthogonal in order for the software to receive correct information. This was not attainable with the aforementioned setup, so two replacement sensors were purchased – a triaxial rate gyro and a triaxial accelerometer. This new inertial package was slightly more compact and could be fitted on the user's wrist.

Combined with inertial data, the magnetic tracker data could be smoothed with only about a fifth of its typical lag, roughly 30 milliseconds rather than 150 milliseconds. Also, the accurate velocity and acceleration measurements enabled better extrapolation of the hand position. Extrapolation is required to compensate for delays of 30 to 60 milliseconds in the image generator, and to extrapolate the hand position to determine which switch is selected.

The magnetic and inertial tracking data are combined in software using Kalman filtering, a technique often applied in multi-sensor navigation systems. The computational requirements of the filter are just within the capabilities of a 200 MHz personal computer, although they could be reduced with more optimization.

3.3 Robotic Mechanism

The starting point for selecting a robotic mechanism was to consider off-the-shelf devices such as industrial robots. The robot must position a payload having an assortment of controls together with the motors necessary to reposition the rotary controls and toggle switches. An initial estimate was that the payload would weigh about five kilograms, although the ultimate design totaled about eight kilograms -- a consequence of the stainless steel construction.

Industrial robots were available which meet the requirements, but they are large, high powered, and expensive. Industrial robots are designed to have a long reach into a large workspace, and consequently are built with heavy links which in turn must be driven by powerful drive mechanisms. Cockpit instrument panels are wide and fairly high, but the panel surface does not encompass much depth. A custom robotic device was designed to take advantage of the restricted workspace. It cost less and is safer than an industrial robot.

The large reach of the industrial robot would have posed a safety problem. Potentially, the robot could move respectable masses at high speeds into the space of the user. Since it would not be acceptable to operate only with software limits the robot would have to be physically modified to make it impossible to travel into the user's space. The customization required would further added to the cost of the device.

Finally, industrial robots are not typically made of non-magnetic stainless steel. Making a new device permitted constraining the design to be compatible with magnetic tracking. In a new design, the electric motors could be positioned as far away from the trackers as possible.

The manipulator design recalls some of the design features of an old-fashioned pen plotter [Figures 3.3-1 and 3.3-2]. The horizontal and vertical axes are driven by Kevlar^{TM} cables. Using cables for both drive mechanisms avoids making the outer axis motor bear the burden of having to move the inner axis motors. Both major axis drive motors are affixed to the frame, one on either side, near the ground, and back from the trackers. A relatively small motor, which moves the payload in and out, is carried with the payload. The electronics cabinet, which houses the servo electronics and system power control and safety circuitry, can be seen to the left of the user [Figure 3.3-2].

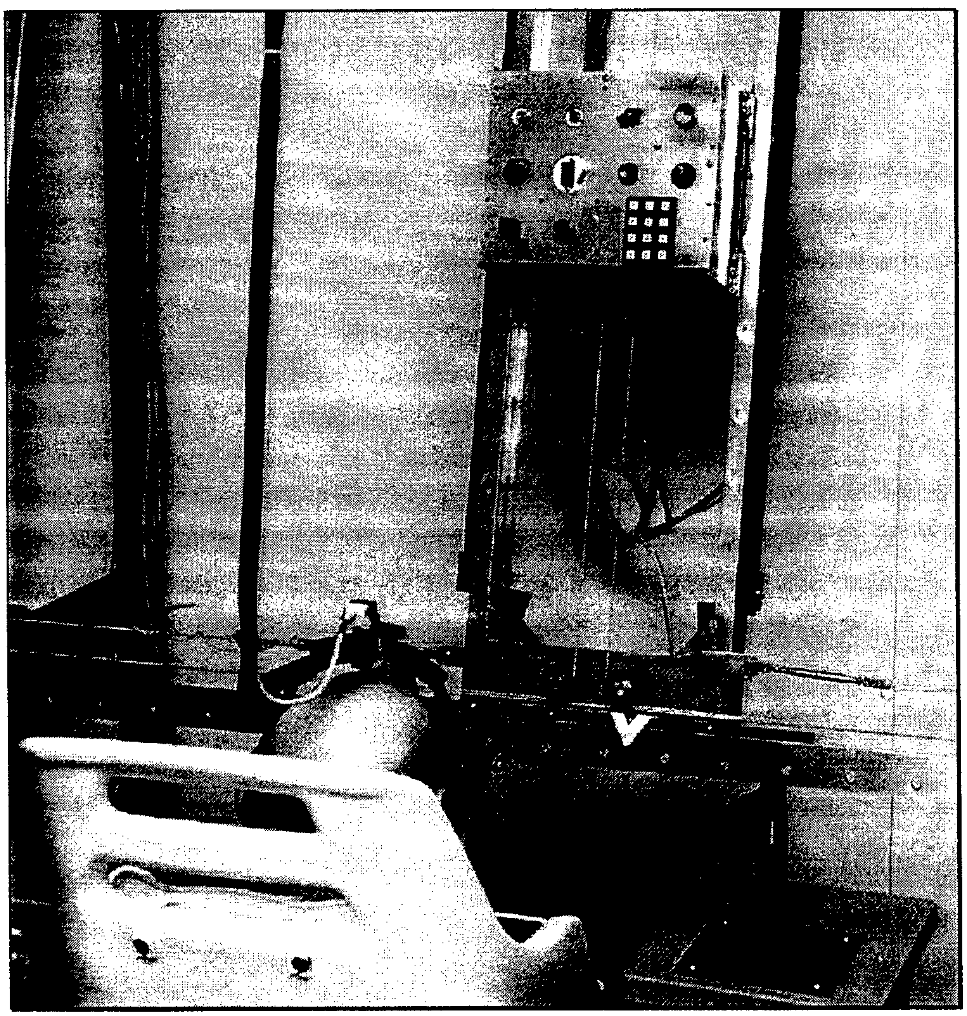

Figure 3.3-1 TOPIT system showing operator's station, X-Y manipulator, and touchboard.

Figure 3.3-2 The final design uses cables to position the switch payload in x and y axes.

The main design feature for safety is constraining the user and the robotic mechanisms to their own workspaces. The user must cross into the robot's workspace to touch the payload controls, but the hand is tracked and the software is designed to bring the mechanism to a halt before the hand crosses into the mechanism area. Still, one must account for possible software failures, for untracked parts of the user's body, and for bystanders. These additional safety provisions are discussed in section 4.5.

In the current design only the head and the right hand are tracked. Tracking the left hand is mainly a cost issue, and doing so would allow controls to be actuated with either hand as well as enhancing safety. The untracked left hand is required to be kept on the throttle. A switch on the throttle must be continually depressed; if it is released the mechanism halts. The throttle switch tends to keep the user properly seated away from the mechanism. A second switch could be added to the seat back to further ensure the head is kept back from the mechanism; leaning forward would release the seat switch and stop the mechanism.

The payload [Fig. 3.3-3] moves with maximum speed about equal to a hand moved laterally to activate a switch. This is not fast enough to cause a serious injury if, due to a system failure, it were to hit the user's hand in motion. A potential danger lies in pinch points, where the users hand might be caught in a closing space between the frame and the payload or traveler. Pinch points are prevented by making the frame oversized and mounting rubber blocks to stop mechanical travel short of the frame.

An emergency stop circuit is included in the design. This circuit is hardwired to a single relay that disconnects and then short-circuits the drive motors, quickly bringing the mechanism to a halt. When the virtual cockpit is in operation, an observer can actuate one of two emergency stop switches if the user or a spectator gets too close to the mechanism.

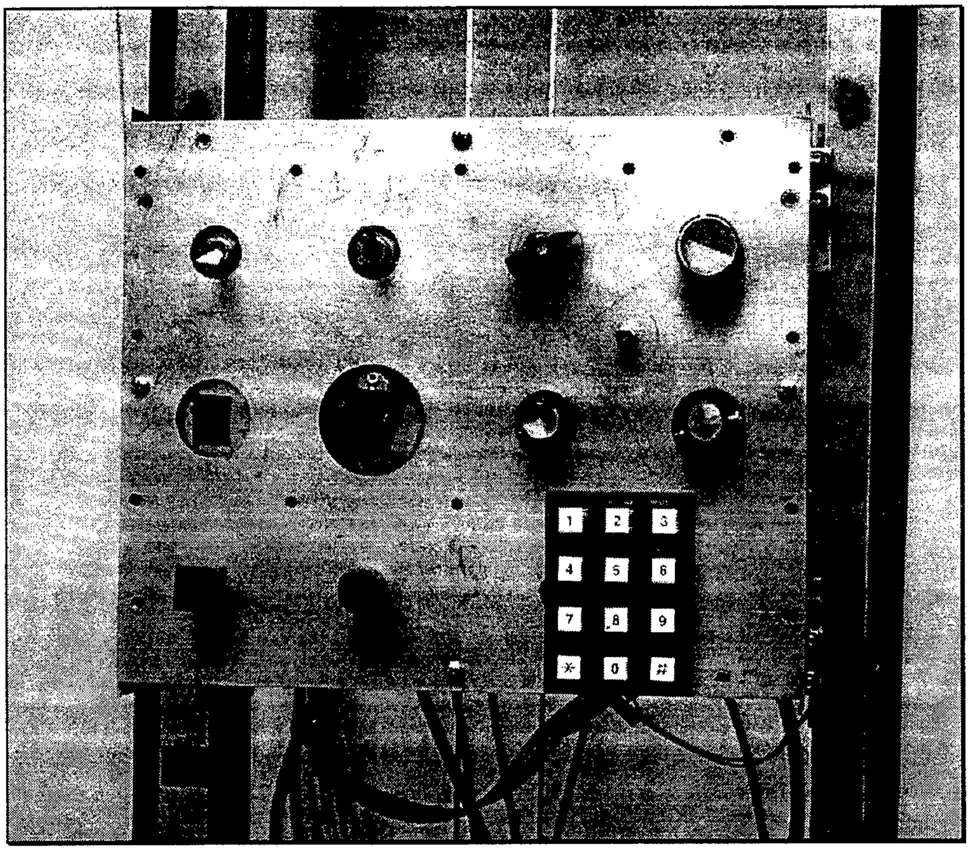

Figure 3.3-3 The payload includes switches and knobs which are rotated to the needed orientation.

Covers would be added to any production device to prevent a bystander from reaching any of the drive mechanisms from the sides or rear of the device.

3.4 Visual Simulation

The Onyx RealityEngine2 computer uses position data from the tracker to prepare the visual scene from pre-stored polygon models of the cockpit, the user's hand, and the out-the-window terrain [Fig. 3.4-1]. The Onyx computer runs a real time version of UNIX in two processors, and we wrote the visual simulation using Silicon Graphic's Performer application package.

There is a delay of one to two video frames in generating the image, marked from the time position data arrives in the tracking computer until the generated image is displayed to the user. The image is generated to correspond to where each moving element of the scene is expected to be at the time when the image appears. Consequently, the position and orientation of every moving element in the scene must be extrapolated forward from the time at which the position and orientation of the element were measured to the time at which the image appears. Simple extrapolation using velocities and accelerations works adequately for times up to about 100 milliseconds.

The imagery is presented to the user on a head-mounted display. Separate images are computed for each eye to provide true stereo. The user's judgment of his hand position relative to the instrument panel is helped significantly by having stereo imagery.

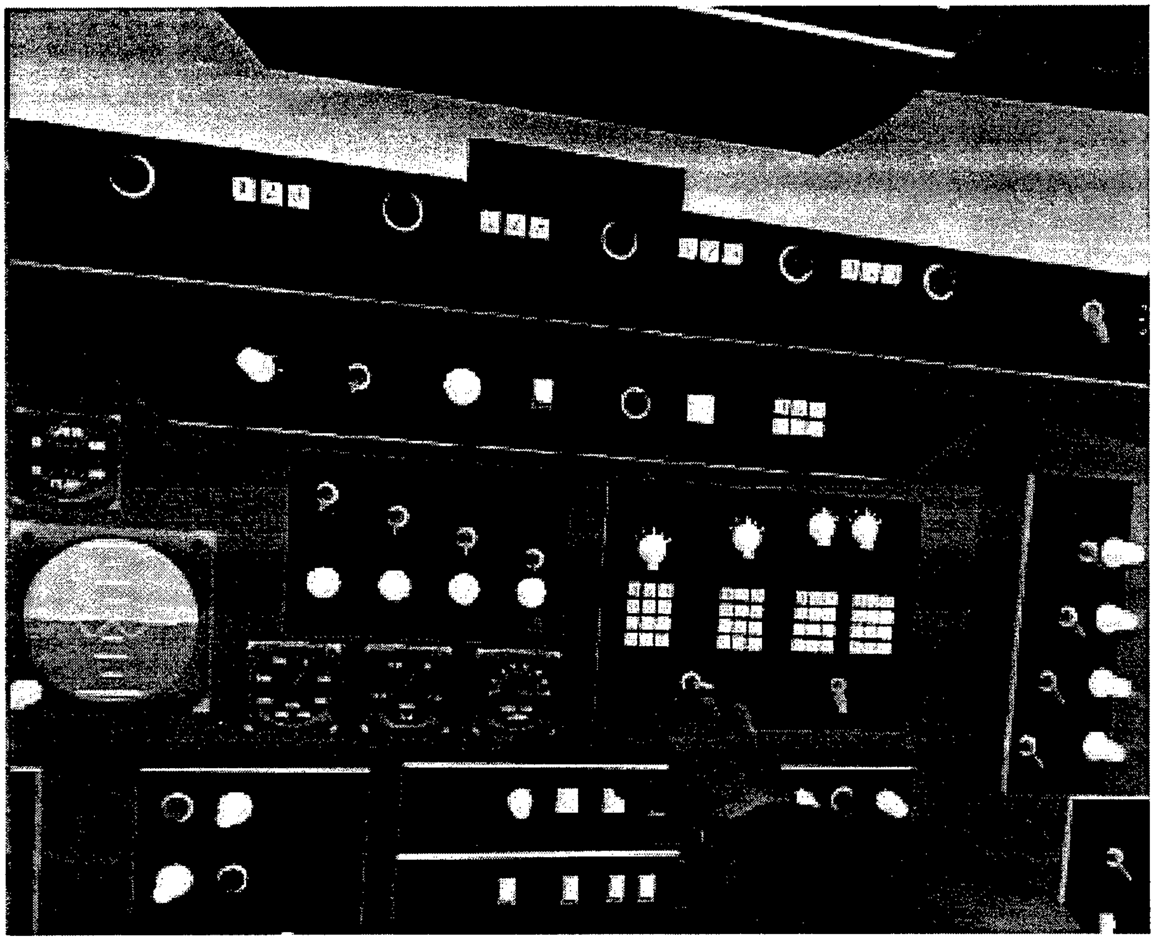

Figure 3.4-1 Generated imagery includes the user's hand.

A moderately priced liquid-crystal based head-mounted display is used, the Virtual Research VR-4. This HMD provides a resolution of about 320 x 480 pixels. This resolution is adequate to see and grasp the controls, but it is not sufficient to read either normal-sized control labels or many instrument panel displays. The compromise in resolution was forced by the economics of the prototype. High resolution head-mounted displays are expensive, and the increased resolution requires more expensive image generation capability. In the development system, the emphasis was on demonstrating the feasibility of the force and tactile feedback mechanism rather than the display.

The polygon processing capacity of the image generator (about 220K polygons per second) limits the scene complexity. The use of stereo imagery cuts the scene complexity in half relative to what it would be otherwise. The cockpit interior is inherently complex, with the knobs and switches modeled in three dimensions. The desired frame rate is at least 30 frames per second, and the allowable polygon complexity per frame is lowered in proportion to the frame rate.

The technology of HMD's and image generators is advancing rapidly, so that these system elements are expected to be less of a limiting factor in the future. The possibilities of advancing technology was part of the reason for partitioning the tracking and visual simulation subsystems around separate computers. The partitioning was designed to simplify substitution of lower-cost image generation technology without having to recode the PC-based tracking computer software. The partitioning could also help in making the hybrid magnetic and inertial tracker with its Kalman filter into a separate PC-based subsystem for other applications.

3.5 System Integration

The system as described is currently working well enough to demonstrate the feasibility of the concept, although there are improvements to be made. A few of the lessons learned in system integration can be cited.

Initially, the software was designed so that the payload would be moved to mirror the position the hand until the hand was within a few inches of the surface of the virtual instrument panel. When the hand reached the pre-determined close distance, the software would pick the switch to be grasped, put the switch into place, and freeze the payload position until the switch was actuated and the hand withdrawn.

The error in this design soon became apparent. The robotic system is designed to accelerate the payload at up to 4 Gs. When the hand was still distant from the panel, the attempt to mirror the position of the hand with the payload produced a great deal of pointless violent motion of the payload. The cure was to put an extra filter on the position data given to the robotic subsystem. The extra filter has a time constant which is adjusted to provide smoother position following when the hand is further from the virtual instrument panel.

Another unanticipated problem was resonance in the mechanical frame of the positioning mechanism. The total weight of the traveler mechanism and the payload is approximately 44 pounds. When accelerated at 4 Gs, the resulting reaction force is therefore about 176 pounds. The frame is welded from 2 inch square stainless steel tubing and is very stiff.

However, tracking movements of the hand produces frequencies which excite resonances in the structure. When resonating, the deflections at the corner of the structure may be as much as a centimeter. It is not clear if the deflections actually degrade system performance, but the fear is that they affect the servo control loops. The shaking is also disturbing to bystanders. Custom pampers were added across the diagonals of the structure to dissipate the resonant energy.

A shell, floor, and an integrated pilot's seat were added to the frame for aesthetic reasons. A compartment underneath the pilot's seat was also built to house the sensor electronics.

3.6 Future VR Systems/Phase III Applications

Forethought in system partitioning and timing analysis, as well as making tradeoffs among the limitations of subsystems are central to good virtual reality systems design. Systems with human/robotic interaction inevitably pose serious safety considerations. With present technology and experience, it is feasible to build a limited class of virtual reality systems, such as the virtual cockpit, to provide force and tactile feedback.

Robotic positioning systems

The concept of robotic positioning of touched objects is not a universal solution to the problem of providing force and tactile feedback. It applies when there is a limited class of objects to be touched, when fidelity is important, when the simulation of external forces is important, and when safety constraints can be met. Alternative methods include special gloves having air bladders or other touch stimulating transducers, exoskeleton devices attached to the hand or body, and robotic devices continuously attached to specialized tools for simulating the forces encountered in the tool use.

Within its realm, the method of positioned objects does offer interesting possibilities. Note that in the virtual cockpit, the system could easily provide the capability for touching the window glass or the flat surfaces of the cockpit surfaces. In an architectural walk-through or entertainment system, the user might touch various surfaces of the environment, presented by a robot having a selection of surfaces. The performance requirements for the robotic mechanism in a walk-through environment are different from the virtual cockpit. The larger workspace might dictate something closer to an industrial robot design, but larger surfaces and slower user motion could relax the speed requirements and make the system safe.

A robotic system could also initiate contact. Consider a virtual reality entertainment system with a "dungeons and dragons" scenario. A user wearing a head-mounted display explores dark passageways. At a critical juncture, the user hears a sound from behind and at the same time a robotic device reaches out with a rubber finger to deliver a poke in the ribs. There is potential for such systems.

Hybrid tracker

The hybrid filter could be commercialized by itself. It would need to be smaller and lighter weight. The hybrid sensor module uses two types of sensors; accelerometers and angular rate sensors. The accelerometers available today seem suitable but the angular rate sensors are bulky and relatively heavy. For the hybrid tracker to be smaller and lighter alternative angular rate sensors are needed. There are several sensor companies already working on better angular rate sensors but suitable products are not currently available - perhaps in a year or so.

A commercialized hybrid tracker, along with the Kalman filter software we developed, would make a great add-on to commercially available magnetic trackers produced by Ascension and Polhemus by providing an accurate low lag tracking system. Many aerospace and commercial applications would benefit from such enhanced performance.

4. Phase II Results

W have accomplished all of our objectives. A picture of the final system and snapshots of subsystems and components is presented in section 1. Detailed evolution results of each subsystem, compared against the objectives, are described in the following.

4.1 Positioning System

Project Objective #1: *Build a positioning system that moved fast enough but without excessive size, power, or cost.*

The positioning system includes the X, Y, and Z axes of motion. To move fast enough to keep up with anticipated user motions, the TOPIT™ had to accelerate at 4 Gs and move at 100 inches per second in both the X and Y directions. The rates were achieved in both axes even though the weight of the payload exceeded expectations. Two oversights, a miscalculation of the drive drum diameter and the effects due to gravity, previously prevented the Y axis from attaining this specification. The incorrectly sized drive drum was corrected by designing, fabricating, and installing a larger diameter drive drum. The effects due to gravity were compensated by using a coil spring attached by one end to the frame and the other end around the new drive drum.

A significant technical achievement in the X, Y motion control was the successful implementation of motion control software which not only controls the servos in such a way that the payload is transported to its commanded location in minimum time without overshoot but also coordinates X and Y motions such that straight-line X-Y motions are achieved. Straight-line motions minimize the demand on the servo power supply by reducing the commanded acceleration and speed on the axis with the shortest distance to travel such that the X and Y motions take the same amount of time to complete.

We incorporated a variable gain filter on X/Y motions so that the servo system responds to hand motions more slowly when the user's hand is more than a few inches from the payload. The filter is progressive; the further away the user's hand, the slower the response. Highest performance moves (high speed and high acceleration) are only needed for final payload positioning when the user's hand is approaching the payload. General tracking is all that is required otherwise.

To achieve X and Y drive performance and minimize the required power and cost it was necessary to minimize the weight which had to be moved. The Z drive motion is attached to and moves with the payload by the X and Y drive motors. In an effort to save weight and achieve desired performance in the X and Y directions a motor was chosen for Z drive. Initially, we had some mechanical difficulty in setting up the Z drive correctly. After a redesign of the linear bearing and ball screw assembly, the Z drive now works well; although, the maximum travel is limited to four inches rather than the specified six inches.

Since we planned to build a virtual aircraft cockpit the overall size of the TOPIT manipulator frame was dictated largely by the application. One design goal of the project was to have the ability to simulate an aircraft cockpit dashboard area 42 inches wide by 30 inches high. We achieved horizontal (X direction) excursions of 42 inches but safety concerns and the need to allow emergency stopping areas above and below the payload limited vertical excursions to about 22 inches - still sufficient for proof-of-concept testing. We believe the overall size of the device could be made somewhat smaller by repositioning turnbuckles used to tension the X and Y drive cords and by repositioning several of the pulleys used by those cords. A somewhat different payload and touchboard design where the touchboard (the switch panel on which the user controls are located) is partially cantilevered would increase the vertical excursion without compromising safety.

The following subsections describe the evolution of the system. While the various efforts are discussed sequentially, the reader should note there was considerable overlap in these efforts.

4.1.1 Desktop prototype hardware development and testing

To confirm our motor calculations, verify our bearing choice, and to provide a means of testing the magnetic tracker compatibility we decided to build a single axis desktop prototype on which performance with loads of up to 25 pounds were tested. The prototype used a custom workbench-like structure that was constructed of wood so that it would not produce magnetic interference. Initially the tracks for the wheels were made of steel. We also tried aluminum and stainless steel tracks later. Testing suggested we needed to use non-magnetic (series 300) stainless steel for the proof-of-concept system. The load was moved using low-stretch Kevlar cords and a series of pulleys connected to a drum which in turn was direct-coupled to a two-horsepower servo motor.

We originally planned to use v-groove wheels and track. The quality of the wheel bearings and the wheels themselves turned out not to be satisfactory so we used cam followers, which have heavy duty roller bearings, for the wheels and aluminum channel for the track [Figure 4.1-1]. Note the turnbuckles which are used to tension the Kevlar cords.

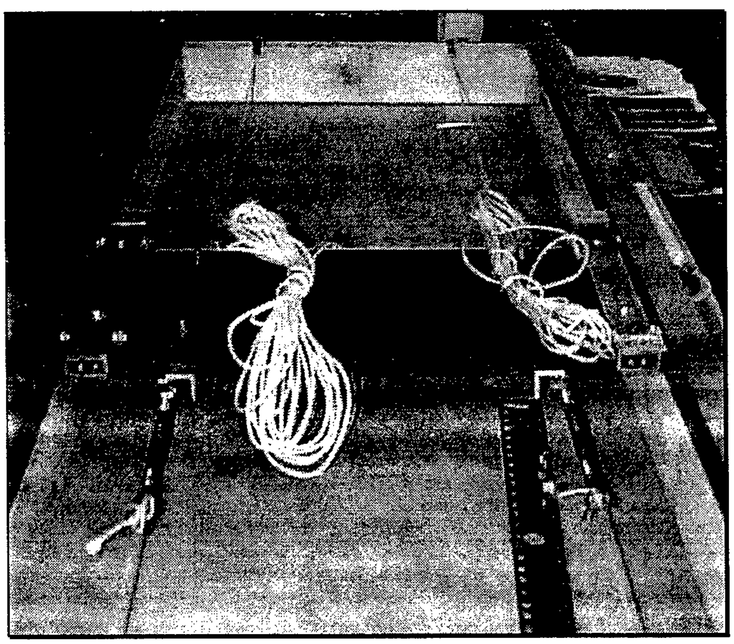

Figure 4.1-1 Desktop prototype with cam followers used for wheels and aluminum channel used for the track.

The drive mechanism [Figure 4.1-2] was located underneath the desktop. Note the hand crank, which was used for initial testing, the drive drum, and the Kevlar cord wrapped around the drum.

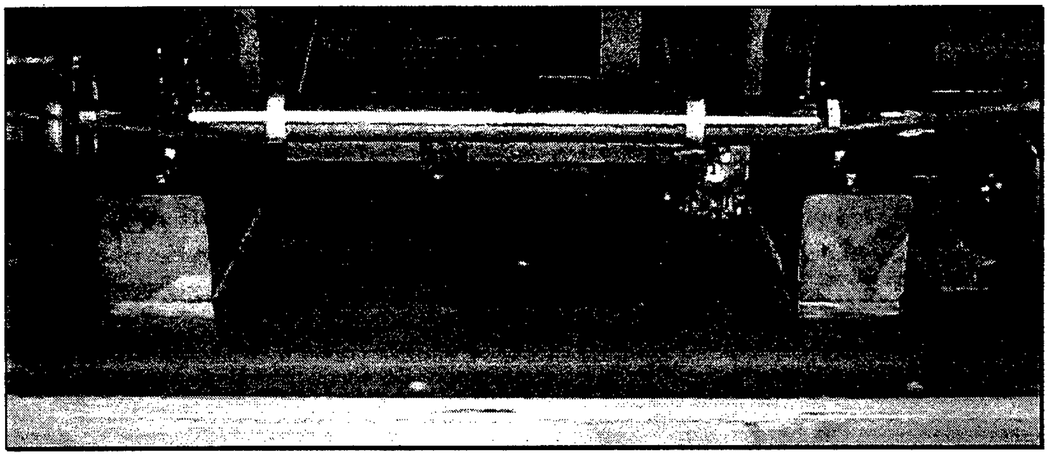

Figure 4.1-2 The desktop prototype drive mechanism.

After receiving all the necessary components and completing construction of the desktop prototype it was wired to the servo electronics and testing began. The safety system was verified to be working correctly. The homing sequence was programmed and verified; the homing sequence is the process by which positioning is automatically calibrated by moving the payload so as to actuate switches at each end of the device. We also determined the sliding carriage could be positioned with an accuracy of 1 mm or better over its travel - more accurate than needed.

The ultimate requirement for the system is to provide 4 Gs of acceleration and 100 inches per second velocity with a payload of 25 pounds. A piece of scrap iron was used as the load on the desktop prototype [Figure 4.1-3].

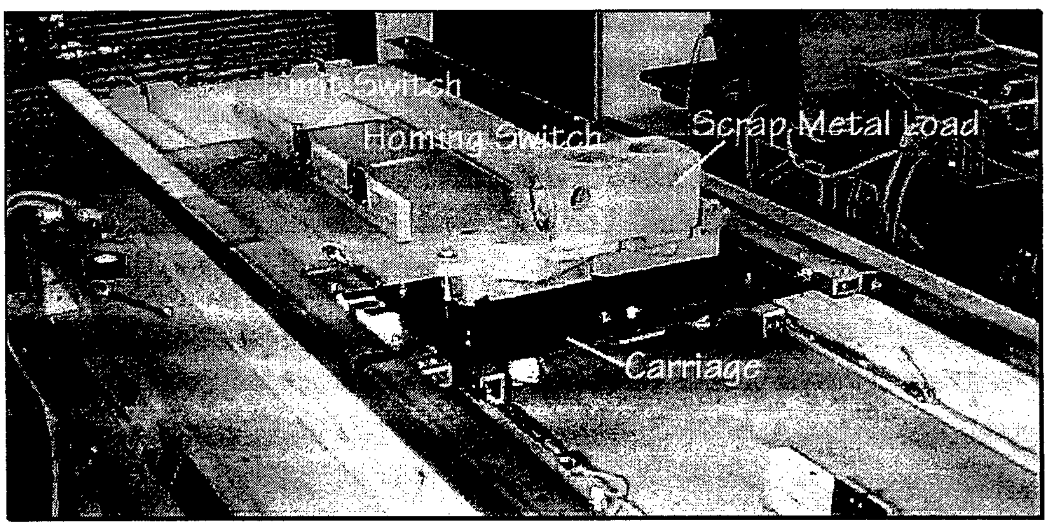

Figure 4.1-3 Desktop prototype with scrap metal load.

The test envelope was first expanded to 1 G of acceleration and 100 inches per second velocity without additional payload weight. As testing progressed we identified and cured the various problems that surfaced. Many of these problems would have occurred later on the proof-of-concept system had we not first discovered them on the desktop prototype. We therefore believe the desktop prototype effort to be worthwhile since it uncovered problem early in the program allowing more time to correct them before construction of the proof-of-concept device. Several examples of problems encountered follow.

First, there was more friction in the unloaded transport mechanism than we expected. We changed the cable pulleys to a larger type with better bearings and that helped, but did not reduce the friction to our expectations. The motor is powerful enough to easily overcome the transport friction, but we still wanted to reduce it further and experimented accordingly.

Second, servo power amplifier shut itself down short of providing all the power we needed to achieve 4 Gs of acceleration. We decided the protection limits were set too low, so we expanded them without risking the amplifier. We later upgraded the amplifier to allow it to handle greater loads.

Third, there was some concern with the motor starting to heat up during continuous operation. This turned out not to be a problem.

We were concerned that Kevlar cable used in the drive transport might creep or be too stiff but later concluded the Kevlar cable worked well.

We observed motion oscillation before settling at high loads. This was cured by correctly tuning the motion control software to account for the "as built" mechanical stiffness of each axis of motion. Such tuning is typical of a servo systems and Delta Tau (manufacturer of the PMAC motion controller card) provides software specifically designed to permit such tuning.

Test objectives for the desktop prototype were established and software written to support the testing needed to accomplish the objectives. Desktop prototype test objectives and test results are discussed below:

1) Verifying operation of the limit-switch safety system

The limit switch system worked reliably and correctly.

2) Verifying the homing and position calibration sequence

The homing and position calibration software worked reliably and correctly.

3) Identifying sources of friction and loading in the transport mechanism

Excess friction was traced to the bearings in the cable pulleys. Higher performance pulleys were installed, and this significantly reduced the friction.

4) Establishing ways of checking and maintaining component alignment

A four-turnbuckle system was installed and has proved suitable for alignment. However, the approximately six inch length of each turnbuckle reduced the usable active area of the desktop prototype by almost a foot. A more compact turnbuckle mechanism, where the mechanism overlaps with the width of the payload carrier, was designed and installed. It worked fine and provided about twelve additional inches of payload travel.

5) Checking the positioning accuracy and repeatability

The positioning accuracy is better than a millimeter, and we had no problems with the cable stretching or slipping on the drum. We need only about 3 - 5 millimeters accuracy.

6) Establishing the acceleration and velocity limits of 4 Gs and 100 inches/second

After a few problems with amplifier shut down and amplifier failures we achieved the design goal of 100 inches per second for large excursions of the manipulator. We also set a second design goal of 4 Gs for small excursions. Both of these goals were met with a 22 pound load - nominally the load to be carried by the "X" axis (horizontal).

7) Checking for design limits, such as potential motor heating, in continuous operation

The payload was cycled for several minutes at 4 Gs acceleration - a time duration far in excess of normal operation. Motor heating was not a problem but the extended duration of maximum acceleration testing caused one of the amplifier IGBTs to fail. The amplifier has subsequently been upgraded and we have not had any other failures.

8) Rechecking all of the design parameters with half and full payload weights

Rechecking the design parameters with half and full loads was completed.

In the process of exercising the desktop prototype several other concerns arose; selection of a slider material suitable for the X and/or Y axes, audible system noise, and Kevlar drive cord stretch. Our efforts in these areas are discussed below.

We tested several types of slider material. We were looking for a durable low friction material. We found that Teflon-loaded Delrin sliding against a stainless steel track worked reasonably well. The concern was that the plastic would gall, which is what happened when we tried nylon against aluminum. However, the Delrin did not gall nor show signs of wear in our tests, even though the stainless steel track material used for the tests was not finished as smoothly as one would like. The final product would have a smooth finished track. Based on the success of these tests, we used the Delrin/stainless steel combination for the y-axis slider in the final design for the proof-of-concept demonstrator.

We noticed the system was noisier than we would prefer when the payload moved. We thought this noise might be distracting to a user even if the user was wearing a headset. We determined the noise was due to the steel payload wheels riding on the aluminum channel we were using as a guide.

The moving mechanism was modified to reduce the noise. The steel wheels running in the channels were replaced with simple flat plastic pads (made from high density polyethylene). It was much quieter in operation and potentially lighter weight. We were concerned about potential wear and monitored it as testing continued - the plastic surface showed some galling after operation. Pads were required facing each of the three sides of the channel to keep the slider from twisting under high accelerations. There was more friction with the plastic than with the wheels. Spraying the inside of the aluminum channels with silicone lubricant reduced the friction considerably, but it had to be sprayed fairly often - something like once a day.

Tuning of the servo loop control software was best done with a payload which moved smoothly with uniform resistance to motion. Since the temporary slide mechanism did not provide smooth motion, the payload was outfitted with a wheeled carriage mechanism which was constructed using nylon ball bearing wheels to which rubber O-ring tires were attached [Figure 4.1-4]. While it provided the desired smooth (and quiet) operation of the desktop prototype, it was too bulky for use in the proof-of-concept demonstrator.

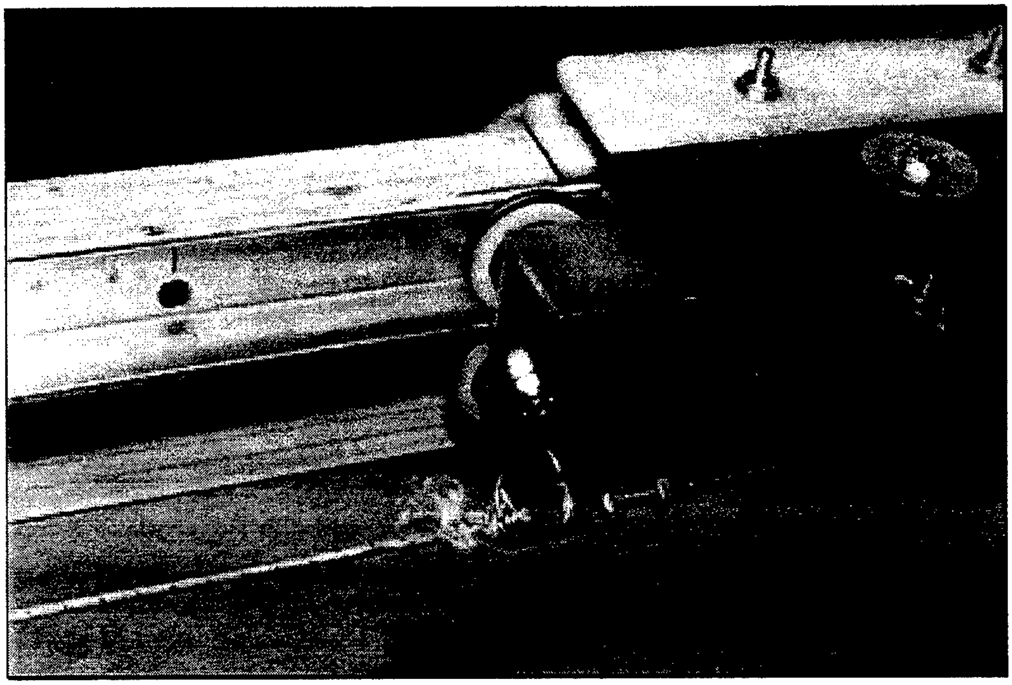

Figure 4.1-4 Portion of the payload and wheeled slider assembly - rubber "tires" on the wheels grip a flange to provide quiet operation.

The desktop prototype was later retrofitted with PTFE slider material (a high-performance plastic material). It was be used in conjunction with stainless steel rails which provided smoother motion than the aluminum rails used with the first set of sliders. The galling we witnessed with the first sliders was also eliminated.

Note that performance of the original steel wheeled arrangement was fine except for the noise generated. Noise is mainly a cosmetic issue. Nonetheless, using plastic sliders had the additional benefits of being lighter and simpler than either of the wheeled arrangements, as well as generating less noise.

We noted we had to tighten the Kevlar™ drive cords periodically. While not a major problem, we looked into the cord stretch problem by conducting some tests. We determined that when in constant use, the cords stretched slightly due to heating. The result was lower than desired cord tension. We also determined that as the cords cooled, they returned to proper tension. We do not believe this condition will exist when used in a true simulation environment where the TOPIT is exercised much less frequently than in our testing scenario. We therefore decided not to take any additional action other than to continue to monitor the situation.

4.1.2 Manipulator design

We define the manipulator as including the X, Y, and Z drives and related hardware. We designed the TOPIT manipulator based upon lessons learned with the desktop prototype. We decided to stay with the cable-driven mechanism used for the desktop prototype, rather than switching to the originally-proposed belt-drive arrangement. The cable (or "string") drive worked fine on the desktop prototype and has the advantage of keeping the servo motor further away from the tracker. We also decided to use cable drive for the y-axis, i.e., the vertical axis [Figure 4.1-5]. This saved the x-axis motor from having to move a y-axis motor. The y-axis motor remains stationary. The y-axis motor is coupled to the Y slider through pulleys.

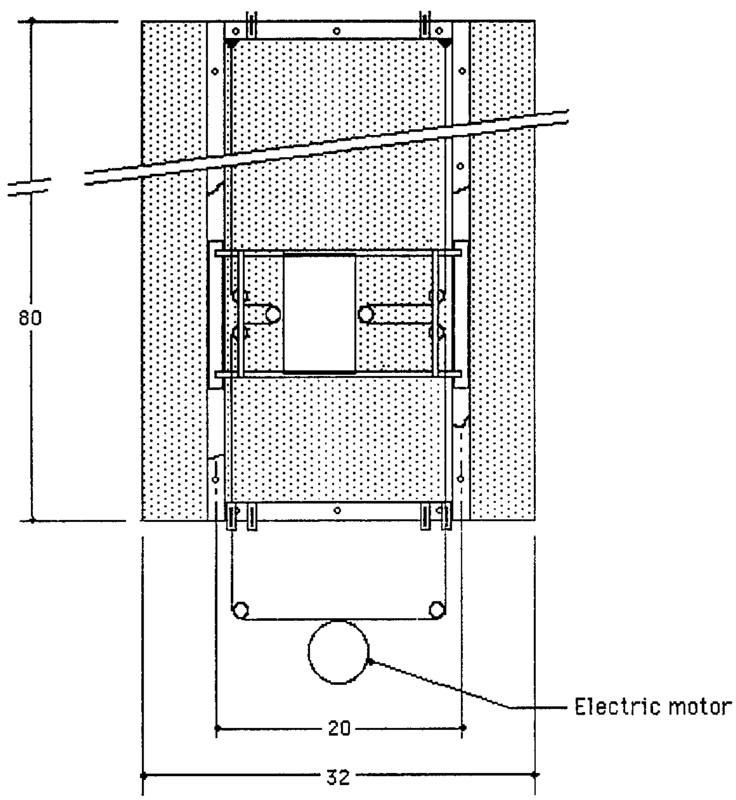

Figure 4.1-5 How a stationary motor drives the y-axis independent of x-axis motion.

We combined the operator station with the manipulator frame design to reduce the overall complexity. By adding brackets to the manipulator frame to hold the operator seat which in turn held the operator hand controls (joystick and throttle) [Figures 4.1-6 and 4.1-7] we eliminated virtually all of the mechanical design effort from the operator station. Since the position of the operator's seat and hand controls are fixed to the manipulator frame, they do not have to be tracked during real time simulation. Note the hybrid tracker attached to the dataglove [Figure 4.1-6].

Figure 4.1-6 Control station with throttle and joystick; HMD rests on seat.

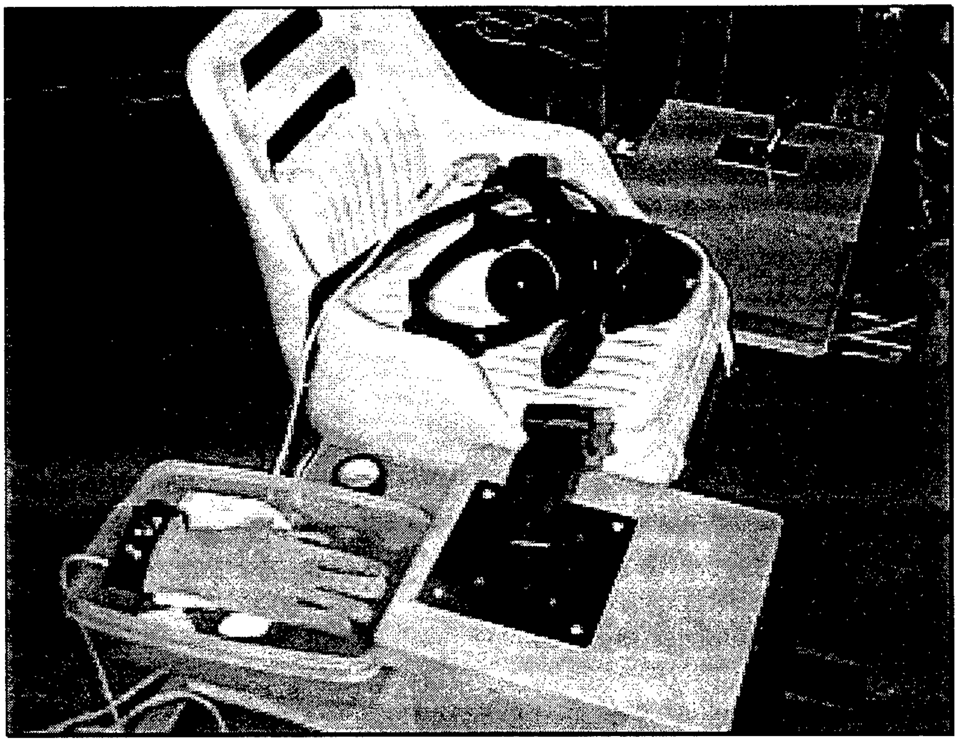

Figure 4.1-7 Control station includes throttle and joystick; HMD rests on seat.

Note the large emergency stop switch to the immediate rear of the user's throttle housing on the left side of the chair [Figure 4.1-7]. The HMD rests on the chair. The dataglove is in a protective box without the hybrid tracker attached.

We decided to make the manipulator with two side A-frames connected by horizontal rails. All manipulator mechanical components were attached to the frame. We used two-inch-square stainless steel tubing for the frame since stainless steel causes much less interference with the magnetic tracker than carbon steel or aluminum. Wood was considered briefly but then discounted since wood is unstable with changes in humidity and it is difficult to produce a sufficiently stiff structure with wood. Stainless steel channels were attached to the frame to support moving parts of the manipulator. Large X and Y-axis drive motors are located at the rear of the manipulator frame to minimize magnetic interference with the user's tracked hand [Figures 4.1-8 and 4.1-9]. Note the drive drums and Kevlar drive cords in both figures.

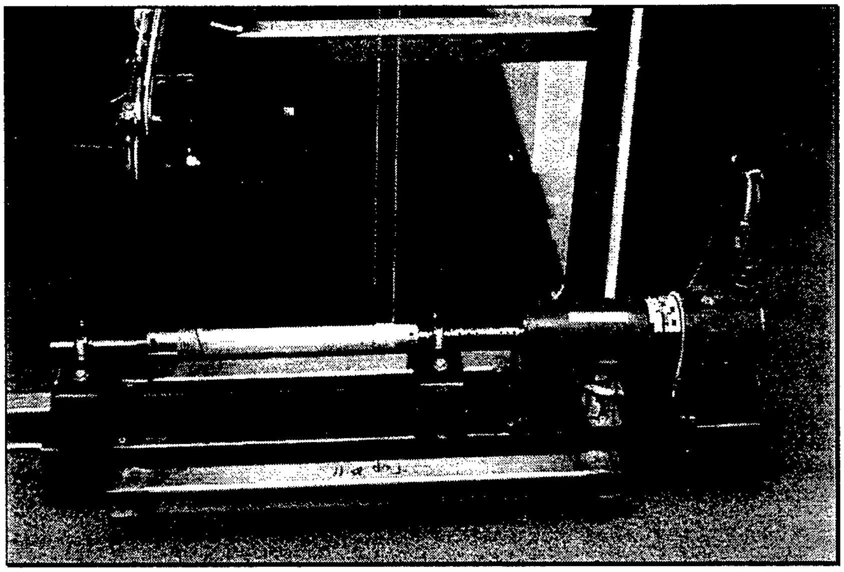

Figure 4.1-8 Lower right side of manipulator frame showing x-axis drive components.

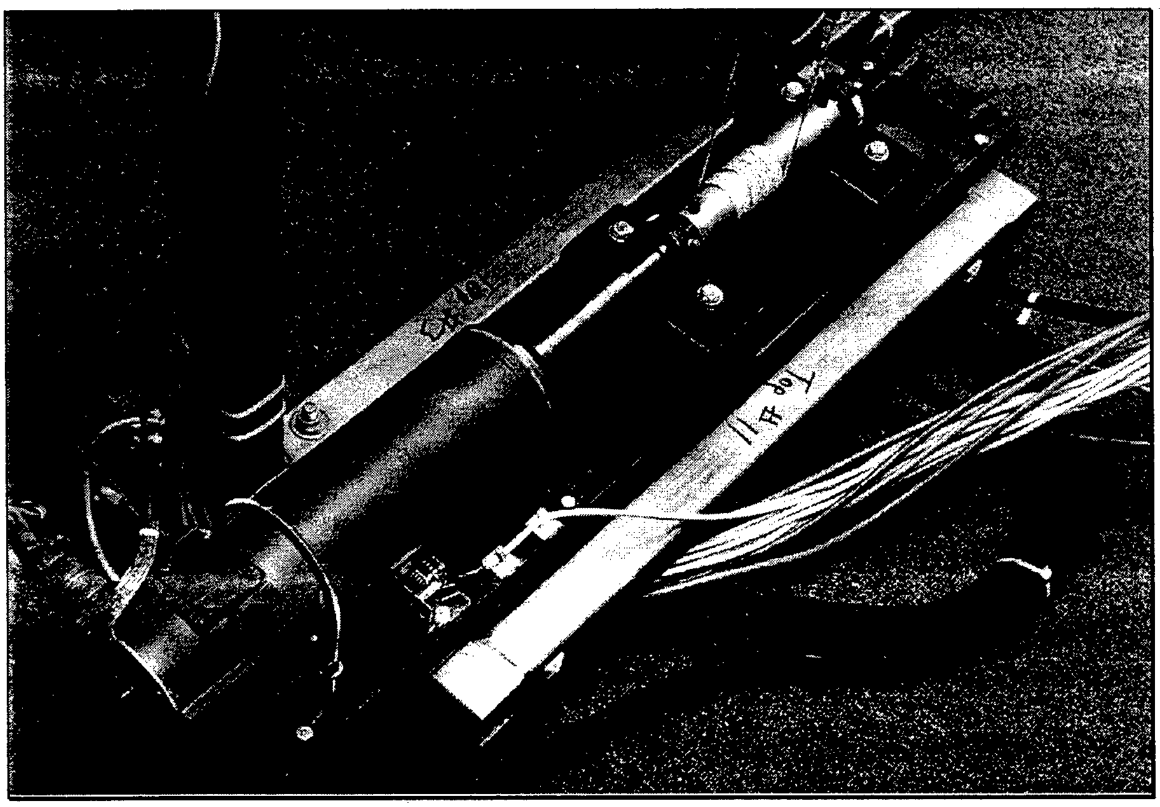

Figure 4.1-9 Lower left side of manipulator frame showing y-axis drive components.

From the drive drums shown above the Kevlar drive cords are routed via pulleys to the payload [Figure 4.1-10]. Cord tension is provided with turnbuckles such as the one shown in the figure.

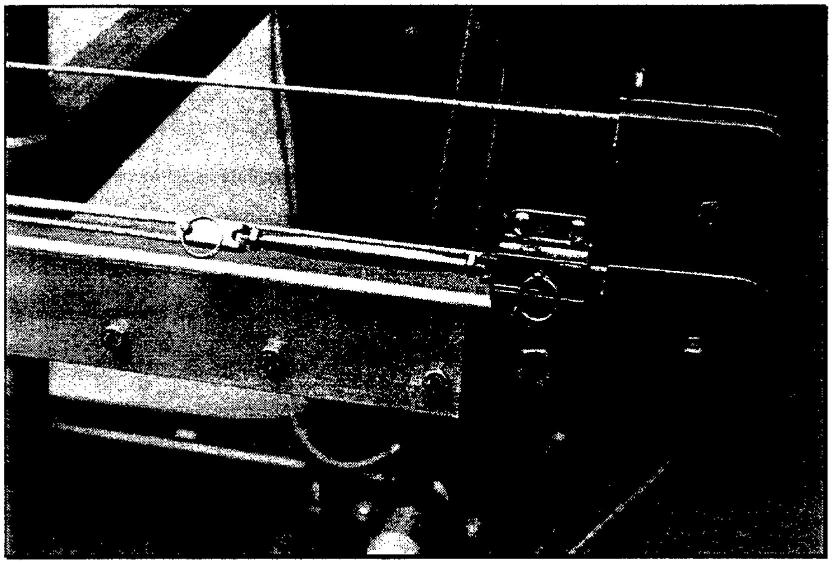

Figure 4.1-10 Manipulator frame showing Kevlar cord, tensioning turnbuckle, and pulleys.

From the pulleys the Kevlar cord is routed to the X traveler (tall vertical frame) and the Y traveler (behind the payload) [Figure 4.1-11]. The X traveler moves horizontally, supported by the manipulator frame at the top and bottom. The Y traveler moves vertically, supported by the vertical side channels of the x-traveler. Graphite composite stiffeners reinforce the x-traveler.

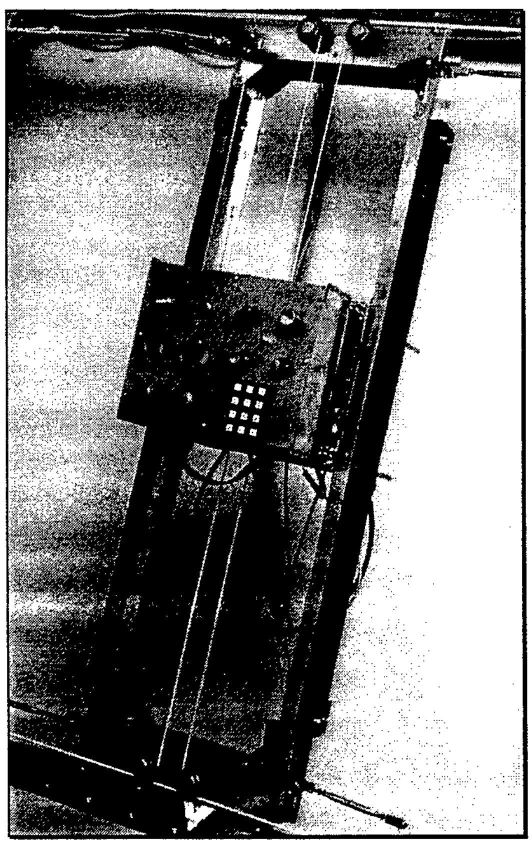

Figure 4.1-11 X-traveler, y-traveler, and payload.

A ball screw drive was adopted for the z-axis. Linear bearings are preferred in applications like this since they provide smooth linear motion but such bearings weigh significantly more and are physically larger than brass bearings. To save weight and space brass bearings were used. Unfortunately, the higher friction produced by the brass bearings in combination with an under-powered (but light weight), z-axis drive motor did not work well. Motion was intermittent and the motor often stalled. With the test experience we now have, we believe the X and Y drives have sufficient power to permit the use of heavier linear bearings and a larger z-axis drive for any follow-on units we might build.

System testing with high accelerations showed undesirable X-axis deflections in the manipulator frame caused by high acceleration moves in the X direction. To cure this problem, we designed a set of dampers for the manipulator frame to reduce the vibration. These dampers are currently under construction and will be installed as soon as construction is complete.

4.1.3 Payload design

We define the payload as including the touchboard (the panel on which all TOPIT simulated cockpit controls are mounted) and all associated servos, solenoids, and other hardware. It is the payload which is moved by the manipulator.

Rotary and toggle switches on the payload had to be rotated so that the user would find the switch in the correct position corresponding to the image of the virtual switch in his HMD. A number of alternative configurations of gears and motors that could accomplish the needed rotation were considered. The simplest way would have been to directly rotate each switch, without gearing, [Figure 4.1-12]. In the figure solenoids are used to engage switch détentes under computer control so that switches having different détente spacing could be simulated.

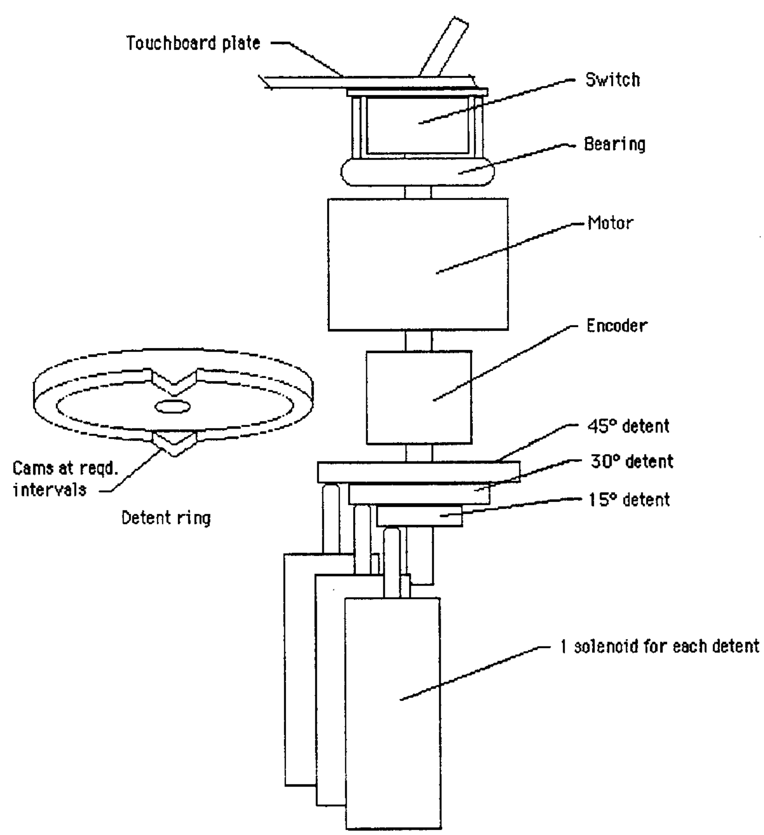

Figure 4.1-12 Direct drive switch rotation with programmable détente positions.

Working from the sizes and weights of the various switches and the properties of motors, the design implications of the alternatives were studied. Table 4.1-1 shows an example of the calculations we did for a particular motor and gear configuration.

Table 4.1-1 Payload design calculations.

Switch	Average Switch Speed (rad/sec)	Switch acceleration (rad/sec^2)	Average motor speed (rad/sec)	Motor acceleration (rad/sec^2)	Armature torque (oz. in..)	Friction torque (oz.in.)	Load torque (oz.in.)	Motor torque required (oz.in.)
A1	7,200	10,048	7,200	10,048	1.68	0.17	3.25	5.10
A2	7,200	10,048	7,200	10,048	1.68	0.17	2.75	4.59
A3	7,200	10,048	7,200	10,048	1.68	0.17	0.55	2.40
A4	7,200	10,048	7,200	10,048	1.68	0.17	0.37	2.21
B1	5,400	7,536	5,400	7,536	1.96	0.28	7.63	9.87
B2	5,400	7,536	5,400	7,536	1.96	0.28	7.63	9.87
B3	5,400	7,536	5,400	7,536	1.96	0.28	7.63	9.87
B4	5,400	7,536	5,400	7,536	1.96	0.28	7.63	9.87

The rotary switch portion of the payload is a mechanism that moves selector switches and continuous rotary controls (like volume controls) into the angular positions to which they were last set by the user. The user must find each control in the correct angle and with the correct détentes and stops for that control. A motor turns the control to the correct position and a set of solenoids selects the détentes. A second motor (not shown) selects the stop angles for the selected rotary control. The stop motor controls the extreme left and right control rotation angles.

In many ways the rotary control portion of the payload design is the most demanding, because a complex mechanism must be put in a small space. To save weight, a single motor and solenoid mechanism was geared to drive four rotary controls. Only one of the four rotary controls can be accessed at any one time by the user, so it makes no difference that the other knobs linked by gears happen to be rotating in unison.

4.1.4 Control software development

At the beginning of the project, we shared some of the assets of this contract with the *STRICOM SBIR A94-062 3-Axis Locomotion Simulator Study* contract for basic motion control software development efforts. Basic motion control is common to both projects. The servo electronics were connected to a servo motor we installed in a commercially available treadmill. The treadmill was used to demonstrate single axis control for the *SBIR A94-062* project. Control software developed for the treadmill demonstrator was modified for use on the TOPIT.

Treadmill demonstrator control software accepted tracker position data which indicated the treadmill user's position on the treadmill and adjusted the speed of the treadmill to prevent the user from walking or running off either end of the treadmill. User tracking was first done mechanically with a "stick" tracker - a piece of wood with one end attached to an encoder and the other end held by the treadmill user. The stick tracker was sufficient for its purpose and served us well during our initial motion control experiments.

Efforts then progressed to the Ascension magnetic tracker later in the effort. Software which phase locks the PMAC operations to those of the PC were also developed and proven with the treadmill demonstrator. This phase locking software was directly applicable to the TOPIT.

Safety software was added limit the speed and acceleration of the servo motor. The safety software serves two purposes. It limits the speeds and accelerations to avoid damaging the servo and drive mechanism, and it protects the user from high accelerations that might cause a loss of balance. Initially, the limits were set low to protect the user. As we got the tracking and control algorithms perfected, the envelope of the treadmill performance was expanded to accommodate more vigorous acceleration, running, and stopping.

Initial motion control testing on the desktop prototype was done with user input directly to the PMAC via an encoder [Figure 4.1-13] . The encoder (upper left in the figure) mounted temporarily in the electronics cabinet was used to provide a temporary, electrically noise-free source of hand position tracking. Next we drove an analog input to the PC with a potentiometer to check the PC/PMAC interface. We then drove the system with the magnetic tracker input to the PC. Subsequent testing used the Multi-Sensor Hybrid Tracker (discussed below). This gave us the ability to move the tracker and have the desktop demonstrator payload follow. This step-by-step checkout procedure allowed us to thoroughly check each component before adding another uncertainty to the system.

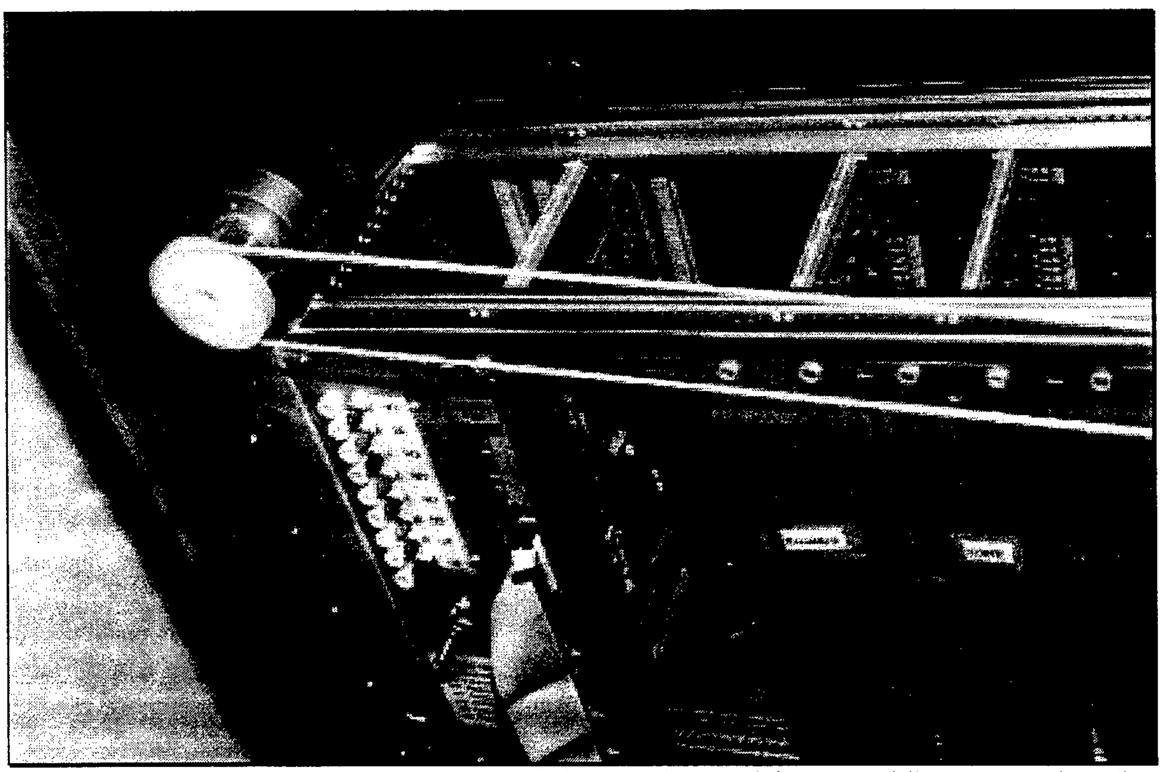

Figure 4.1-13 Portion of the electronics and the encoder used for initial "string tracking" tests - the string loop extends to the prototype fixture and slider motion tracks the string position.

To get best performance from the system it was necessary to tune motor performance to the actual masses and spring constants of the respective motor loads. Delta Tau, manufacturer of the PMAC motion control card we are using, provides a set of software utilities for this purpose.

4.2 Tracking System

Project Objective #2: ***Ensure the tracking system provided sufficient accuracy in the presence of electromagnetic noise and moving metal objects.***

Our hybrid tracker consists of a commercially available Ascension Flock of Birds magnetic tracker combined with a custom six degree-of-freedom inertial tracker. The magnetic tracker produces both position and attitude data but, to minimize inherent noise, data averaging of many sequential data points is used. This averaging process introduces a time lag in the position and attitude data sent to the computer. A second problem with magnetic trackers is their susceptibility to interference by metallic objects - particularly those containing aluminum, steel, or iron.

To solve the lag problem we constructed a hybrid tracker by adding inertial tracking to the magnetic tracker. The inertial tracker measures X, Y, and Z linear accelerations as well as rotational accelerations in roll, pitch, and yaw. Kalman filter software running in a Pentium Pro 200 is used to combine the data from the magnetic and inertial sensors to provide accurate, low lag hand position and attitude information for the simulation.

4.2.1 Hybrid tracker development

We ran some preliminary experiments to determine the tracker's susceptibility to interference from non-moving steel and aluminum objects. The tracker was also placed near a 2 horsepower electric motor. The motor was turned on and off to roughly simulate what might happen with a servo. The results showed about what we expected: the tracker is quite susceptible to the motor noise. We also ran some additional experiments to determine the susceptibility to interference from non-moving carbon steel, stainless steel, and aluminum objects which were placed nearby. There were several interesting results. First, the tracker exhibits a large error at longer tracker ranges (24 inches or more) and the error is not affected much by nearby non-moving interfering test objects. We also noted that stainless steel test objects had no noticeable affect on the tracker accuracy. We also determined that the shape of aluminum test objects had a large effect on the tracker accuracy.

A detailed list of tests and software required to test the magnetic tracker was prepared. The purpose of those tests was to determine the effect of stainless steel, carbon steel, and aluminum on the accuracy of the tracked position. For this series of tests, test objects were placed at various distances from the tracker receiver and the tracker receiver will be placed at various distances from the tracker transmitter. Test objects included one inch round by two foot long tubes and one foot by two foot sheets of the three metals mentioned above. Test results showed no significant interference with series 300 stainless steel while also showing there was substantial interference with both carbon steel and aluminum and thus confirmed what we had been told by the magnetic tracker manufacturer Ascension.

We looked at ways to overcome the noise susceptibility of the magnetic tracker, and developed an approach which used inertial sensors in conjunction with the magnetic tracker. Inertial sensors, miniature accelerometers and angular rate sensors, provide excellent short-term accuracy that is immune to electromagnetic effects. However, the inertial measurements drift over time, and must be updated with position and angle "fixes" to remove the drift errors.

If magnetic tracker measurements are available occasionally to update the inertial measurements, then we expected the tracking system would perform well over both the short term and long term.

Kalman Filter Software

The Kalman filter software combines the data from all the sensors under consideration to provide a combined "optimal" estimates of position and attitude. The Kalman filter software actually combines data from various sensors continually, weighting the value of each data according to its error characteristics. It works amazingly well. Kalman filter technology has been used in aerospace applications such as aircraft navigation for a long time.

Initially, most of the sensor error models were based on published specifications, but as we collected data the error models were improved.

Kalman filter software requires "tuning" as part of the test process before it will function properly. Tuning is the adjustment of the mathematical models of the sensor error performance to agree with the error performance encountered in practice. Paul worked with one of our student interns to tune the software.

In the development we captured a set of hybrid tracker data for a small set of hand motions: left - right, fore - aft, and a series of rolls. The data were used to tune the Kalman filter software. Rather than sampling data at different times, all of our data is sampled at one instant in time. Changes were made to the software, which was originally designed to sample data at different times, to accommodate the new data sampling scheme and forwarded revised software to CGSD.

Magnetic field calibration software

Despite the use of series 300 stainless steel for most custom portions of the TOPIT the magnetic field of the tracker was still distorted by the presence of solenoids, motor, switches and other non-stainless steel metallic items. To get the needed accuracy from the magnetic tracker in the presence of these items we developed software to map the position dependent magnetic field distortions for the magnetic tracker. The magnetic tracker was attached to the payload. The payload was driven to various positions by custom calibration software. The position and attitude at each grid location was recorded in a table. The contents of the magnetic calibration table were subsequently used by the real time software to determine the actual location of the magnetic tracker.

TEU Hardware

At the time we started development of the hybrid tracker we had three contracts which required advanced tracker technology; this contract, the *STRICOM SBIR A94-062 3-Axis Locomotion Simulator Study* contract, and a commercial contract. We constructed a tracker evaluation unit (TEU) which includes X, Y, and Z accelerometers, roll, pitch, and yaw angular rate sensors, a tilt sensor, and a compass. This module along with custom software was used to select the sensor configuration most appropriate for each of the three applications. A printed circuit board was designed, fabricated, assembled [Figure 4.2-1], and tested. As described above, the TEU has a large collection of sensors and is designed strictly to support lab experimentation. It is too large and has too many sensors for production. However, it is essential for collecting the real data we need to support algorithm development.

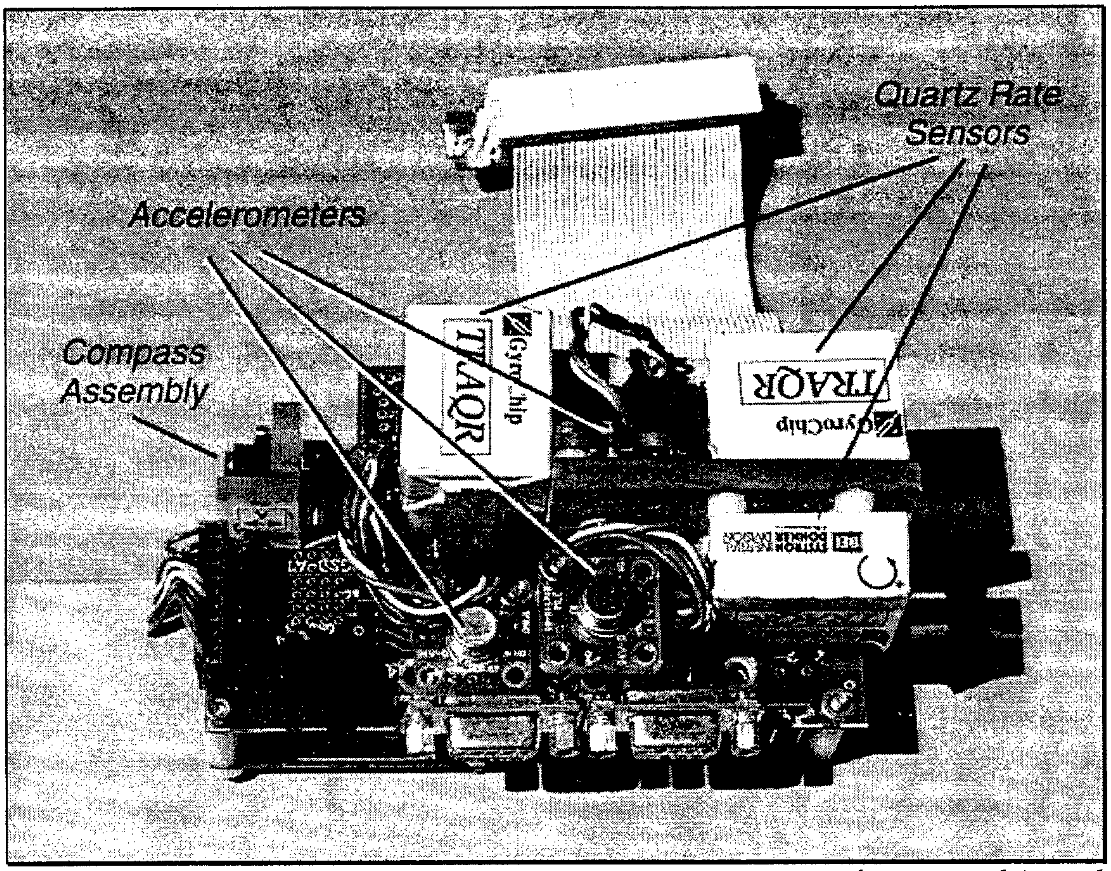

Figure 4.2-1 The Tracker Evaluation Unit contains more sensors than were ultimately selected.

Hybrid Tracker 2 Hardware

We decided to repackage the hybrid tracker so that it would not be as bulky and heavy. The original TEU discussed above contains a compass and tilt sensor which are not required by the TOPIT program. The redesigned unit, called "hybrid tracker 2", consists of two modules; a sensor module shown with the magnetic tracker [Figure 4.2-2] which contains the gyros and accelerometers and the control module for the computer interface. The custom printed circuit board, compass, and tilt sensors used in the TEU were eliminated. The sensor module, which is attached to the back of the glove, is much smaller and lighter than TEU. It is connected to the control module by a single cable.

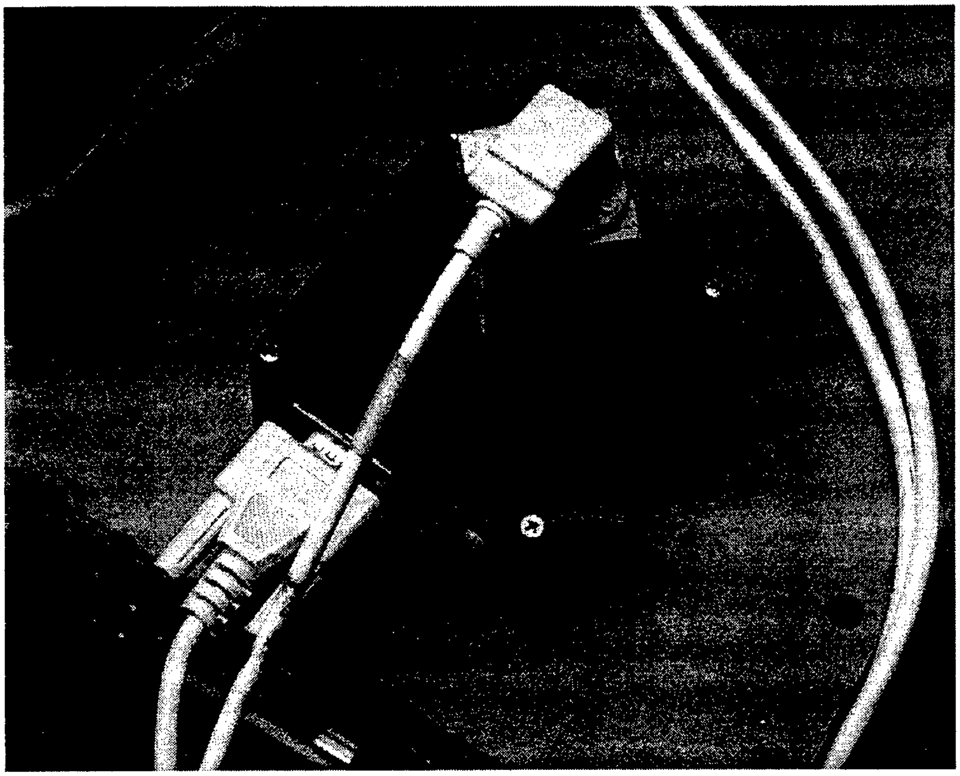

Figure 4.2-2 Hybrid tracker 2 sensor module with magnetic tracker attached.

We believe a production version of the hybrid tracker can be considerably smaller and lighter weight than hybrid tracker 2 shown.

Hybrid Tracker 3 Hardware

Our research showed that the alignment of the sensors in the Hybrid Tracker 2 unit was not acceptable. As a result we integrated two triaxial sensors – a rate gyro sensor unit and an accelerometer sensor unit. This replaced the inertial tracking portion of the Hybrid Tracker 2 unit. We are still using the Flock of Birds magnetic tracker unit. Hybrid Tracker 3 is lighter and has a smaller footprint than its precursors. Signal conditioning hardware, built by one of our student interns, was used to integrate the new sensors with the existing system.

4.2.2 Optical Tracker Development

Since the result of the hybrid tracker is not quite up to our expectations, we are further exploring the optical tracker.

We have installed DynaSight™ sensor (optical tracker by Origin), have written drivers for the optical tracker, and integrated the optical tracker into TOPIT.

Two methods were integrated in order to test the applicability of each. The two methods are described below:

Method 1:

Method one uses a single optical target. The target used was initially just a piece of retro-reflective tape applied to the glove's index finger. Offsets were recalculated for this tracking system and the hand position was backwards calculated from the glove offsets in order to simulate the finger articulations. The hand orientation was read in from the magnetic tracker.

This proved to get rid of some of the position noise as well as problems with the warped magnetic field (caused by the stainless steel frame and the EM fields from the motors and solenoids in the payload); however, after testing, a position hysteresis was found while moving along the X axis of the optical tracker. A constant offset was noticed with constant velocity. This was a result of the sequential (180 degrees our of phase) measurements taken by each optical sensor as it calculated the Z axis.

The retro-reflective tape was exchanged for an active target (IR LED). Integrating the IR LED, the ATA (Active Target Adapter), and the TOPIT™ system was easily accomplished. DIP switches in the back side of the optical tracking unit can be set to use the ATA and IR LED (please refer to the DynaSight™ Sensor manuals).

Method 2:

Method two uses three optical, active targets in order to calculate the hand orientation as well as position. This required writing a driver for the QNX operating system. The ATA integrated easily with the DynaSight™ Sensor (DIP switches must be adjusted. Please refer to the DynaSight™ Sensor manuals). The three active targets were mounted on a triangular plate (supplied by Origin Instruments) and mounted on the CyberGlove.

The purpose of using optical sensors was to increase the position accuracy of the sensors. Without filtering, the position measurements were much less noisy compared to the magnetic trackers. Also, since the optical trackers are not affected by EM waves, the warped field did not affect its accuracy.

Notes in comparing the noise to that of the magnetic tracking unit (MT) are as follows:

Noise reading: (taken on 26 February 1998)
- MT with ALL filters on (lots of lag – unacceptable lag)
  - position: 0.02 inches
  - angle: 0.03 degrees
- MT with ACNarrow filter only (normal operation mode)
  - lag is okay...
  - position: 0.85 inches
  - angle: 1.70 degrees
- OPTICAL (no filtering)
  - lag is okay...
  - position: 0.06 inches
  - angle: 1.45 degrees

Because the magnetic tracker measurements with all of the filters on creates an unacceptable lag, these noise figures are not used as comparison. With the ACNarrow filters on only, the magnetic tracker data contains more noise compared to that of the optical tracker.

Method 1 with an active target (IR LED) is used even though its implementation does NOT output angle information. The reason for this is that the position of the fingertip is given rather than the position of the wrist (as the case would be in Method 2). If the sensor is used to calculate the wrist position, the angle noise would affect the calculated fingertip position. Therefore, Method 1 provides a more accurate solution to the fingertip tracking problem.

4.3 Hand Motion Prediction Algorithms

Project Objective #3: ***Design hand motion prediction algorithms that predict which control will be touched while sufficient time remains to put it in place.***

Software to meet this objective consists of two parts; the hand motion prediction algorithm itself, and the cockpit to real time capture zone software.

Hand motion prediction

The hand motion prediction algorithm was implemented by starting with current hand position and attitude. Predicted positions and attitude is determined by using accelerations and velocities for six degrees of freedom. The general form of the computation, which is performed in all six axes of motion (X, Y, Z, roll, pitch, and yaw), is as shown in equation 1. The hand prediction algorithm is working well.

$$P_P = P_C + V_C T + A_C T^2 \qquad \textit{[Eqn. 1]}$$

where:

P_P = predicted position

P_C = current position

V_C = current velocity

A_C = current acceleration

T = time to predicted position

Zone capture software

It was useful to divide the operating envelope of the virtual cockpit into regions or "zones" that help define TOPIT FTFS manipulator operating conditions and operating actions. The four zones are:

Zone A: A volume ordinarily containing the user, when the user is not accessing any controls on the virtual control panel.

Zone B: A volume outside Zone A extending to within a short distance - about 1.5 inches - of the surfaces of the front of the virtual control panel with its instruments.

Zone C: The volume on the user side of the virtual instruments within a short distance - about 1.5 inches - of the virtual control panel with its instruments but outside Zone B.

Zone D: The volume beyond Zone C, including the surfaces of the controls and the control panel.

Figure 4.3-1 illustrates a cross-section with the various manipulator control zones.

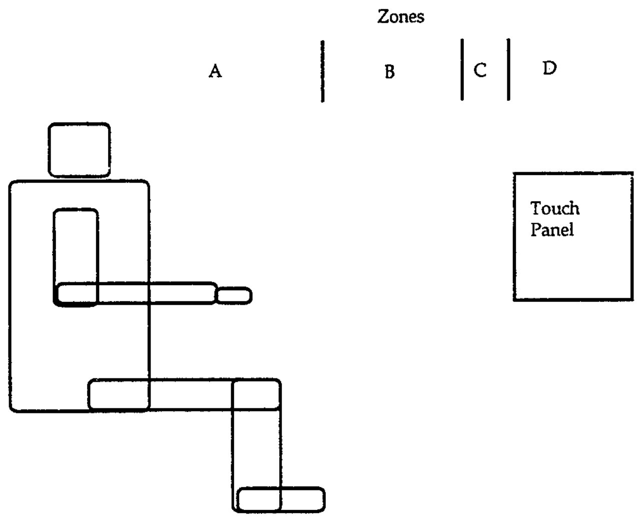

Figure 4.3-1 Manipulator Control Zones.

Note that for the prototype TOPIT, the controls need not lie in a plane. The transport includes a depth axis which allows the virtual control panel to be stepped or even curved. Accordingly, the control zone volumes A-D are mapped to the contours of the cockpit control panel in a lookup table and are not bounded by planes.

The requirements for TOPIT FTFS positioning speed depend upon the position of the user's hand relative to the operating zones described above. Motion requirements for each operating zone follow:

Zone A: When the user's tracked hand is within Zone A, the TOPIT FTFS will not move.

Zone B: When the user's tracked hand is in Zone B, the TOPIT FTFS will move at maximum speed to the mirror point. The mirror point is that manipulator position which is closest to the user's tracked hand.

Zone C: When the user's tracked hand is in Zone C, the TOPIT FTFS manipulator will move at maximum speed. In this zone the computer determines which control the user is reaching for and positions the appropriate control at the correct position in front of the user. The choice made by the computer will be based upon extrapolation of the hand trajectory. The final position of the TOPIT FTFS is not made until the user's hand enters zone D.

Zone D: When the user's tracked hand is in Zone D, the TOPIT FTFS will not move.

The real time capture zone software that provides these functions operates properly.

Early in debug we discovered the need for an additional refinement. As originally implemented, the control software would always attempt to use the maximum performance of the hardware to track the hand. It would accelerate the payload at 4 Gs to follow the hand motion, even when the hand was relatively far away from the simulated panel surface in zone B. The resulting violent motion of the hardware place unnecessary stress on the mechanism, because high accelerations are only required when the users hand is relatively near the panel.

To damp the motion of the payload when the hand is distant, we implemented a variable time constant filter that smoothes the motion tracking. When the hand is far away, the time constant is large and high accelerations are avoided. The time constants are reduced to provide full performance as the hand approaches a control on the panel.

Note that the additional smoothing is not applied to the position used for rendering the image of the hand. The image always react quickly so the user will have a correct view of his hand position. The extra filtering is not applied to the extrapolated hand position used to select which control will be actuated. The extra filtering is only applied to the payload positioning commands.

4.4 Computation Control Lags

Project Objective #4: ***Keep computation and control lags small enough so that the positioning system had sufficient time to position the touchboard.***

The following steps were taken to minimize computation and control lags in the system:

- Dedicated servo controllers were used to provide high computational rates to support the servo loop computations. The loop update rates are over 100Hz.
- True real time operating systems were used throughout: Ultrix, SGI's real time version of UNIX in the Onyx; QNX, a proprietary real time operating system, in the PC; and the PMAC motion control system in the servo controllers. True real time systems allow the user to manage the priorities of interrupts so that time critical events are not delayed in a service queue.
- A dedicated Ethernet™ link was used between the PC and the Onyx. Having a dedicated link avoids latency due to packet collisions, and latency is kept under one millisecond.
- The hybrid tracker provides accurate rate and acceleration data to extrapolate over unavoidable latencies, such as the time in the image generator needed to render the graphics imagery.

Overall, system latencies are quite good, but there are two limitations. First, we could not afford to build a second hybrid tracker for the head mounted display, so there are noticeable lags when head motion is rapid. There is no technical problem in adding a second hybrid tracker. Second, even though a substantial amount of the budget was devoted to obtaining a high performance image generator, and considerable effort was made to minimize polygon counts in the database, the image generator frame rate is at most 30Hz, and it sometimes drops as low as 20Hz. Image generator technology has advanced rapidly, so that now at the end of the two year development program there are available image generators with much higher polygon capacities than the SGI RealityEngine2. For example, the newer Lockheed-Martin Real3D Pro 2000 provides about three times the polygon capacity at one-third the cost of the RealityEngine2.

4.5 Safety Systems

Project Objective #5: ***Provide redundant safety systems to protect the operator during development and use.***

A number of things were done to ensure personnel and equipment safety. Some of these features were discussed briefly in previous sections. These design features, combined with a few common sense procedures have served us well - we have had no injuries on the TOPIT program. The design features and procedures are discussed below.

To ensure the user's head is not hit by the moving payload, should he lean forward for some reason, the user's seat is positioned as far away from the manipulator frame as practical. The seat position still allows the user to activate touchboard controls without excessive leaning.

To ensure the user's untracked left hand is never near the moving mechanism, the user must depress a button on the throttle with his left thumb. If he lets go of the button, real-time software causes X and Y motions to stop (other motions are considered not dangerous). The system must be reinitialized by the system operator before it will move again.

Limit switches on the X, Y and Z axes are used for system initialization [Figure 4.5-1]. Limit switches are located near the ends of the excursions on each axis and are activated if the payload touches them. Limit switches should not be activated during real time simulation, i.e., a motion control error has occurred if they do. If any of these switches are activated during real time simulation, the PMAC motion controller software causes all motions to stop. The system must be reinitialized by the system operator before it will move again.

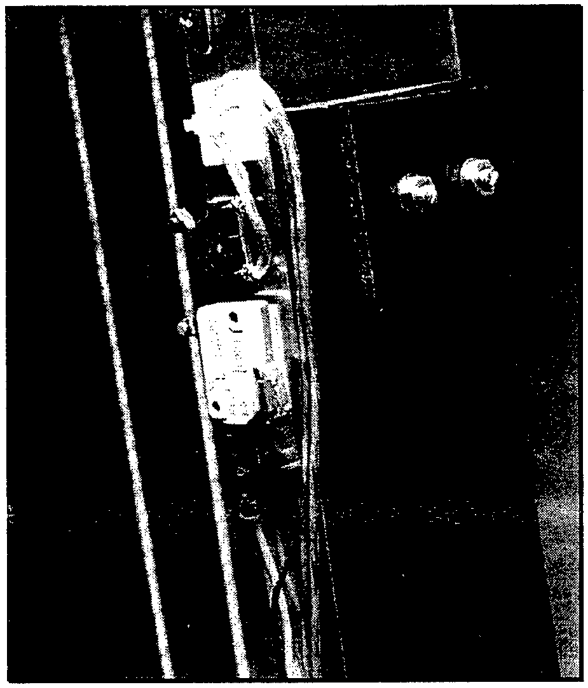

Figure 4.5-1 Typical limit and emergency limit switches.

A set of emergency limit switches is located next to but beyond the X and Y limit switches [Figure 4.5-1]. Should the limit switches or the PMAC software discussed above fail to act for any reason, the emergency limit switches will cause the X and Y drive motor windings to be disconnected from their respective amplifiers and shorted together. This will cause motion in both the X and Y axes to stop immediately. Two manually operated emergency stop switches, one located on the electronics cabinet and one near the user's left hand, can also be used to stop X and Y motion. Manual reset is necessary to reactive the system following such a shut down.

A potential hazard on any mechanical design is sharp edges. These were minimized during the design process. With a moving mechanism, such as the TOPIT, the concern becomes the existence and control of pinch points. We use both bumpers and shields (not yet installed) to minimize personnel exposure to pinch points.

To minimize exposure of the user's tracked right hand to contact with moving parts of the TOPIT we programmed the hand motion prediction algorithms to stop X, Y, and Z motions and freeze the position of the payload when the hand approaches the payload. Payload motion does not resume until the user moves his hand away from the payload again.

A safety light flashes when manipulator power is on. The safety light is positioned so that it can be seen by anyone in the area of the TOPIT (except the user when he dons the HMD).

Turning to procedures, we have a two man rule for TOPIT operation when the user is wearing the HMD and cannot see the manipulator. The second man positions himself close to one of the manually operated emergency stop switches so that he can activate the switch should he see anything out of the ordinary.

To prevent a passer-by from being injured, should a computer glitch cause unexpected manipulator motion, we insist TOPIT personnel shut off manipulator power when they are not in the vicinity of the machine.

5. Conclusions

Overall, the major technical challenges were met. In particular, robotic hardware was built to position the controls with the speed and accuracy required, and a sophisticated tracker and an alternative tracker were built to provide the accuracies required for position and extrapolation. The most difficult aspect of the program turned out to be getting all of the bugs out of the complex system under severe budget constraints. In this last respect we were largely successful, but not entirely. The main limitations of the final prototype lie in the fine points of getting the software to run completely smoothly and reliably. We view none of the present limitation as being fundamental.